Prepared in cooperation with the U.S. Environmental Protection Agency

Geology and Mining History of the Southeast Missouri Barite District and the Valles Mines, Washington, Jefferson, and St. Francois Counties, Missouri

By Douglas N. Mugel

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Cover photograph: Family digging for barite (Witman, 1941), National Archives Catalog

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Suzette M. Kimball, Acting Director

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	61.02	cubic inch (in^3)
	Flow rate	
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
microgram (ug)	0.00000003527	Ounce, avoirdupois (oz)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations and Symbols

GIS Geographic Information System
IMOP Inventory of Mines, Occurrences and Prospects
MGS Missouri Geological Survey
NPL National Priorities List
USEPA U.S. Environmental Protection Agency
USGS U.S. Geological Survey

Geology and Mining History of the Southeast Missouri Barite District and the Valles Mines, Washington, Jefferson, and St. Francois Counties, Missouri

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Abstract

The Southeast Missouri Barite District and the Valles Mines are in Washington, Jefferson, and St. Francois Counties, Missouri. Barite and lead ore occur together in these surficial and near-surface ore deposits and were mined during separate, but overlapping times: lead first, then barite. Lead mining began in the early 1700’s and continued through the 1800’s and into the early 1900’s. Lead mining was by hand and although it was on a small scale compared to modern mines, the Southeast Missouri Barite District was the most important lead-mining district in the United States for a number of years. Lead mining in residuum resulted in widespread areas of small pits, and there was some underground lead mining in bedrock. Zinc occurs in the Southeast Missouri Barite District, but it is not as common as in other lead-mining areas. For this report, the term “lead mining” is meant to be a general term which includes the recovery of zinc in some cases.

The Southeast Missouri Barite District does not include ore deposits of the Valles Mines. There are similarities between the two, but they are different primarily in two respects: 1) most of the mining

at the Valles Mines was in bedrock, in contrast to the Southeast Missouri Barite District where most of the mining was in the residuum; and 2) unlike the Southeast Missouri Barite District, the Valles Mines was an important zinc-producing area, and barite was not as important as in the Southeast Missouri Barite District.

Barite was mined from the residuum using similar hand-mining methods for many years, also resulting in widespread areas of diggings but not underground mines. Mechanized strip mining of barite began in the 1920's. Missouri led the United States in barite production in most years from 1885 to 1971, and most of the Missouri barite production was from the Southeast Missouri Barite District. There has not been any barite mining since 1998. Mechanized barite mining resulted in large strip-mined areas and tailings ponds, which contain the waste product from barite mills.

The U.S. Environmental Protection Agency (USEPA) has determined that lead contamination of residential surface soils and groundwater occurs in Washington and Jefferson Counties. To provide information that would be helpful to the USEPA in determining the source of soil and groundwater contamination, the U.S. Geological Survey, in cooperation with the USEPA, investigated the geology and mining history of the Southeast Missouri Barite District and the Valles Mines. A literature review was conducted for this report without any field investigation.

The Cambrian-age Potosi Dolomite is the most important formation for the ore deposits, followed by the Eminence Dolomite. Ore occurs mostly in the residual soil (residuum) derived from these formations, and also in the underlying rock. Barite (barium sulfate) is a primary ore mineral. The primary, and most important lead ore mineral is galena (lead sulfide). Secondary lead ore minerals are cerussite (lead carbonate) and anglesite (lead sulfate) which formed as alteration products of galena. The primary zinc ore mineral is sphalerite (zinc sulfide); smithsonite (zinc carbonate) is a secondary mineral that also was mined as an ore mineral. Because galena, sphalerite, and barite are less soluble than dolomite, chemical weathering of the dolomite bedrock resulted in the concentration of ore minerals in the residuum, and almost all of the barite mining and most of the lead mining was in the residuum. Galena was sometimes found in masses as large as several hundred pounds.

Lead mining in the Southeast Missouri Barite District and the Valles Mines was primitive by modern standards, and production at individual mines was small compared to the underground mines of the Old Lead Belt and Viburnum Trend. Early lead mines were “diggings” (also called “pits” or “shafts”) in the residuum and normally were round holes about 4 ft in diameter and 15-20 ft deep dug with pick and shovel. The process was repeated a short distance away, until a large area was covered with pits. Later, shafts were sunk into bedrock as deep 170 ft.

Smelting of the lead ore to elemental lead was first done using a log hearth, also called a log furnace, and later ash furnaces, Scotch hearths, and air furnaces were later used. Log furnaces were inefficient; it has been estimated that only about 50 percent of the lead in the ore was recovered, the remainder lost to the ashes (slags) and to volatilization. It has been estimated that the recovery of lead was about 80-90 percent for both the Scotch hearth and the air furnace, but estimates of less recovery have been made for each type of furnace.

The total production from the Southeast Missouri Barite District and the Valles Mines is estimated at 180,000 tons of lead and 60,000 tons of zinc. An estimated 97,000 tons of lead was lost during processing, with a volumetric equivalent of a cube of lead about 65 ft on a side, or a football field of lead 5.7 ft high. An estimated 120,000 tons of zinc was lost during processing, with a volumetric equivalent of a cube of zinc about 81 ft on a side, or a football field of zinc about 11 ft high.

Barite mining in southeastern Missouri was active by at least the 1860’s. Mining was by hand in the same way as earlier lead mining, and increased after 1905 as more uses for barite were developed, with the peak of hand mining during the period from 1905 to the 1930’s when several thousand people were engaged in barite mining. An important development occurred around 1926 when barite began to be used as a weighting agent (drilling mud) for oil well drilling. Mechanized strip mining of old barite diggings began in 1924 to recover barite left behind by hand mining. The barite ore went to washing plants where log washers were used to clean the clay from the barite and jigs were used to concentrate the barite. Overflow from the log washers was waste and went to a mud (tailings) pond. The coarse jig tailings went to tailings piles or were used as railroad ballast, and later roads, within the mine pit. Some barite was ground, depending on its final use, and some ground barite was bleached using a hot solution of sulfuric acid to remove impurities such as iron minerals and lead sulfide (galena).

The total production of barite from the Southeast Missouri Barite District and the Valles Mines is estimated to have been about 13.1 million tons. Most of the barite production was from Washington County. Hand mining and processing of barite was inefficient; estimates of barite recovery from hand mining range from less than one-fourth to about half, as “pillars” between the shafts in the residuum needed to be left unmined for stability. With mechanized mining, large amounts of barite were lost during the milling process. It has been estimated that about 30% of the barite was lost, and that about two-thirds of the lost barite was fine-grained and was discharged to the tailings ponds with the “slimes”, the remainder being larger-grained barite that also was lost during processing. Some galena was lost to the tailings ponds.

A 1972 inventory of tailings ponds by the Missouri Geological Survey identified 67 ponds in the Washington County Barite District; there are currently more than this number documented in the study area. Four of the ponds were sampled using a drill rig, and samples were scanned using X-ray fluorescence spectrometry. It was estimated that the 67 ponds contained almost 39 million tons (or yards) of tailings averaging about 5% barite, for a potential reserve of 1.935 million tons of barite.

The ore deposits contained lead (and zinc) minerals as well as barite. It is not known how much lead was removed during barite mining, either by hand or mechanized mining and processing, how much lead was recovered, or how much lead went as fines to the tailing ponds or as coarse material to mine roads or was otherwise lost.

Introduction

The Southeast Missouri Barite District and the Valles Mines are in Washington, Jefferson, and St. Francois Counties, Missouri (fig. 1). Barite and lead ore occur together in these surficial and near-surface ore deposits and were mined during separate, but overlapping times: lead first, then barite. Lead mining began in the early 1700's and continued through the 1800's and into the early 1900's. Lead mining was by hand and although it was on a small scale compared to modern mines, the Southeast Missouri Barite District was the most important lead-mining district in the United States for a number of years (Ball, 1916). Although lead and barite were mined from the Valles Mines, it is known more as a zinc-producing area. Lead mining in residuum (residual soil) resulted in widespread areas of small pits (also called "shafts" or "diggings"), and there was some underground lead mining in bedrock. Barite was discarded with other waste material for many years until the mid 1860's when it became economically important. Barite was mined from the residuum using similar hand-mining methods for many years, also resulting in widespread areas of diggings. Some barite occurs in bedrock, but was not mined except in cases where accompanying lead made the operation profitable. Mechanized strip mining of the residuum for barite began in the 1920's, and by the 1940's all barite mining was mechanized. Barite mining continued for many years, and more barite was produced than lead. Barite production slowed by the 1980's, and there has not been any barite mining since 1998. Missouri led the United States in barite production in most years from 1885 to 1971 (Missouri Department of Natural

Resources, 2012). Mechanized barite mining resulted in large strip-mined areas and tailings ponds, which contain the waste product from barite mills.

Figure 1. Map showing location of study area, Southeast Missouri Barite District, Valles Mines, Franklin County Mines, and subdistricts of the Southeast Missouri Lead District.

The U.S. Environmental Protection Agency (USEPA) has determined that lead contamination of residential surface soils occurs in Washington and Jefferson Counties at concentrations exceeding health-based screening levels. Also, elevated concentrations of barium, arsenic, and cadmium in surface soils have been identified, and private drinking-water wells have been identified with lead concentrations exceeding the federal drinking water standard of 15 micrograms per liter (ug/L). Potential sources of contamination are mine wastes associated with barite mining, mine wastes associated with lead mining, or natural occurrences of barite, lead, and other metals. To provide information that would be helpful to the USEPA in determining the source of soil and groundwater contamination, the U.S. Geological Survey (USGS), in cooperation with the USEPA, investigated the geology and mining history of the Southeast Missouri Barite District and the Valles Mines in Washington, Jefferson, and St. Francois Counties, Missouri.

Purpose and Scope

The purpose of this report is to describe the geology and mining history of the Southeast Missouri Barite District in Washington, Jefferson, and St. Francois Counties, Missouri and the Valles Mines in Jefferson and St. Francois Counties, Missouri (fig. 1), with particular attention to information that may help the USEPA determine the source of soil and groundwater contamination. Included in mining history are mining methods and mine production, as these may be important factors for soil and groundwater contamination. Early mining of lead or later mining of barite or zinc may have contributed to soil and groundwater contamination.

The main focus of this report is the widespread surficial or near-surface ore deposits of the Southeast Missouri Barite District. The Valles Mines is a smaller area of mines, and is a less important subject of this report. Three subdistricts of the similar-sounding but geologically-distinct Southeast Missouri Lead District – the Irondale and Indian Creek Subdistricts and one mine of the Viburnum Trend Subdistrict (fig. 1) – occur in Washington County and because the USEPA Washington County Lead District includes all of Washington County, these subdistricts also are described, but in substantially less detail. The underground Pea Ridge iron mine and tailings lake in northwestern Washington County is not described in this report.

Both barite and lead mining are described in this report. Although the two resources commonly occur together as part of the same ore deposit, the mining history of each is different. Included in the discussion of lead mining is zinc, which was also recovered from some lead mines but was generally secondary in importance to lead. An exception to this is the Valles Mines where early lead mining was followed by mining for zinc, which was the more important resource there. A literature review was conducted for this investigation, without any field investigation.

Description of the Study Area

The study area is all of Washington County and Jefferson Counties, and northern St. Francois County in southeastern Missouri (fig. 1). The study area contains the ore deposits and historic mines of the Southeast Missouri Barite District, the Valles Mines, and the Irondale and Indian Creek Subdistricts and one mine of the Viburnum Trend Subdistrict of the Southeast Missouri Lead District, and the Pea Ridge iron mine (fig. 2). Ore deposits of the Southeast Missouri Barite District do not occur everywhere in Washington County, but because the deposits are widespread throughout the county and because the USEPA Washington County Lead District is the entire county, all of Washington County is included in the study area. The USEPA Washington County Lead District is divided into four USEPA sites that have been listed on the National Priorities List (NPL) by the USEPA: Old Mines, Richwoods, Potosi, and Furnace Creek (the remainder of Washington County; fig. 2). The USEPA Southwest Jefferson County Site (fig. 2) also has been listed on the NPL. Although the focus of this site is the approximately southwestern quarter of Jefferson County, the entire county is part of the site, with the exception of the lead smelter at Herculaneum (fig. 2), and therefore the entire county is part of the study area. Northern St. Francois County is included in the study area because ore deposits of the Valles Mines and the Southeast Missouri Barite District occur there close to the Jefferson County border, and, in the case of the Valles Mines, overlap both counties such that production figures for the two counties cannot be separated. Ore deposits of the Old Lead Belt Subdistrict of the Southeast Missouri Lead District also occur in St. Francois County, but not in the study area (fig. 1).

Figure 2. Map showing the study area, Southeast Missouri Barite District, Valles Mines, and U.S. Environmental Protection Agency sites in Washington and Jefferson Counties

The study area is a mostly rural area with only a few small cities (fig. 2). Potosi is the largest city in Washington County and was the center of much of the historic barite and lead mining in Washington County. Arnold is the largest city in Jefferson County; De Soto is the closest city to most of the mining in Jefferson County. Bonne Terre is the closest city in St. Francois County to the Southeast Missouri Barite District and the Valles Mines, but is not in the study area; it was the site of important mines of the Old Lead Belt Subdistrict of the Southeast Missouri Lead District.

Areas of mine diggings occur throughout the study area, a legacy of early barite and lead hand mining. Large areas of mine waste, including mine tailings dams and ponds, which contain mine waste from more recent mechanized barite mining, occur in the study area. Also, a mine waste pile and a tailings lake are present at the closed Indian Creek mine of the Indian Creek Subdistrict of the Southeast Missouri Lead District, and an underground mine and tailings lake are present at the Pea Ridge mine in northwestern Washington County. The mine site of the underground Viburnum No. 29 mine of the Viburnum Trend Subdistrict of the Southeast Missouri Lead District is in southwestern Washington County (fig. 2).

Definition of the Southeast Missouri Barite District and the Valles Mines

The geologic and mining literature contains various formal and informal names for the surficial and near-surface barite-lead deposits of Washington, Jefferson, and northern St. Francois Counties that are the subject of this report. The concept of formal mining-district and -subdistrict names appears to not have been considered by the earliest authors. Areas of early lead mining have been informally called the “lead mines of Missouri” (Schoolcraft, 1819), the “lead mines of Washington County” (Ball, 1916; Swallow, 1855), the “lead mines of Jefferson County” (Swallow, 1855), and more formally as the “Washington-Jefferson County Subdistrict of the Southeastern District” (Winslow, 1894). When referring predominantly to barite mining, the area has been called the “Washington County Barite District” (Seeger, 2008; Brobst and Wagner, 1967; Brobst, 1958; Tarr, 1918; Wharton, 1972, 1986; Wagner, 1973), or the “Southeast Missouri Barite District” (Kaiser and others, 1987; Wharton, 1986). Snyder (1968a) describes the “Southeast Missouri Barite-Lead Deposits” as a “barite-lead district”, referring to the barite-lead deposits mostly in Washington and Jefferson Counties, but also minor deposits in adjacent counties.

The term “Southeast Missouri Barite District” is used in this report despite the fact that it has only barite in its name and not lead, which was mined for almost 150 years before barite was mined. Although the term “Southeast Missouri Barite-Lead District” would more completely describe the resources that were mined, the term “Southeast Missouri Barite District” is a term that is already in use, and avoids confusion with the nearby, similar-sounding Southeast Missouri Lead District. There was more production of barite than lead from the Southeast Missouri Barite District, but lead mining was important, and the district can be regarded as a barite-lead district.

Ore deposits of the Southeast Missouri Barite District occur throughout Washington County, Jefferson County, and extreme northern St. Francois County. It was difficult to draw a district boundary for this report because the deposits are so widespread; the boundary shown in figures 1 and 2 was drawn for this report to encompass areas where the ore deposits of the district are most concentrated and where they are mostly in the residuum derived from the Potosi or Eminence Dolomites and in these formations, the most important hosts for the deposits (fig. 3). The mostly scattered deposits in the study area outside this boundary are still considered part of the district; these are mostly in formations younger than the deposits within the boundary of the district.

The Southeast Missouri Barite District does not include mines and ore deposits of the Valles Mines. There are similarities between the two, but they are different primarily in two respects: 1) most of the mining at the Valles Mines was in bedrock, in contrast to the Southeast Missouri Barite District where most of the mining was in the residuum; and 2) unlike the Southeast Missouri Barite District, the Valles Mines was an important zinc-producing area, and barite was not as important as in the Southeast Missouri Barite District (Cheryl Seeger, Missouri Geological Survey, oral commun., July 7, 2016). For this reason the Valles Mines is considered a separate entity by the Missouri Geological Survey and in this report. The Valles Mines (also spelled “Valle”) is sometimes referred to as the Valles Mines Group

(Winslow, 1894), and consists of several mines in southern Jefferson and northern St. Francois Counties, near the town of Valles Mines (fig. 2). One of these mines is the Valles (or Valle) Mine, also called the “Big Lode” (Litton, 1855; Winslow, 1894; Valles Mines, Missouri, USA, 2016). Like most other mines in the study area, this mine consists of several shafts, and for this reason the plural of “mine” commonly is used, and the mine is called the Valles Mines. To avoid confusion with the Valles Mines Group, the term “Valles Mines (proper)”, instead of the term “Valles Mines”, is used in this report for the collection of shafts of the Valles Mine; this term was used by Winslow (1894) and Parizek (1949). For this report, the term “Valles Mines” is reserved for the Valles Mines Group, as this is the term commonly used in the literature.

The Southeast Missouri Barite District does not include small lead-zinc-barite and locally copper deposits that occur along and near the Meramec River, mostly in Franklin County but also in Crawford County, most of which are in formations younger than most Southeast Missouri Barite District deposits. These are probably what Snyder (1969a) was referring to as minor deposits in adjacent counties. Winslow (1894) describes the deposits in Franklin County as the “Franklin County Subdistrict of the Southeastern District” (fig. 1). Park (2006) describes these as the “Franklin County Lead District”. Wharton (1986) describes these as the “Franklin County Mines”, and this term is used in this report (fig. 1).

Figure 3. Stratigraphic column of the study area and vicinity, showing formations that host ore deposits of the Southeast Missouri Barite District, Valles Mines, and Southeast Missouri Lead District

Zinc commonly occurs with lead in ore deposits in Missouri and elsewhere. Zinc occurs in the Southeast Missouri Barite District, but it is not as common as in other lead-mining areas. Conversely, zinc was the most important resource at the Valles Mines. Zinc was not recovered during the early years of lead mining in the study area because it was not an important resource at that time. Later, after the value of zinc was recognized, it was recovered at some mines, and was the primary metal recovered in a few mines, particularly the Valles Mines. Because zinc generally was of secondary importance if at all, the term "lead mining" is meant to be a general term in this report, and includes the recovery of zinc in some cases, and in a few cases copper.

Ore deposits of the Southeast Missouri Barite District and the Valles Mines are distinctly different than the ore deposits of the Southeast Missouri Lead District, although Wharton (1972, 1986) considers the Washington County barite deposits to be part of the Southeast Missouri Lead District. The distinguishing features of the Southeast Missouri Barite District are the occurrence of ore mostly in the residuum and to a lesser extent in bedrock (mostly the Cambrian Potosi Dolomite or the overlying Cambrian Eminence Dolomite, with a few deposits in formations overlying the Eminence Dolomite; fig. 3) and the mineralogy, consisting mostly of barite with lead minerals and lesser amounts of zinc minerals. Ore deposits of the Valles Mines differ by occurring mostly in the Potosi and Eminence Dolomites themselves rather than in the residuum derived from these formations, and zinc minerals are the most important (Cheryl Seeger, Missouri Geological Survey, oral commun., July 7, 2016). In contrast, the lead-zinc deposits of the Southeast Missouri Lead District occur in stratigraphically-lower formations (mostly the Cambrian Bonneterre Formation, and less commonly in the upper part of the Cambrian Lamotte Sandstone or the lower part of the Cambrian Davis Formation; fig. 3), are larger, and are lead-zinc deposits that do not contain barite (Snyder, 1968, Snyder and Gerdemann, 1968; Seeger, 2008). The Southeast Missouri Lead District has four large subdistricts (the Old Lead Belt, the Viburnum Trend, Mine La Motte [also called "Mine La Motte-Fredricktown"], and Indian Creek) and the smaller Irondale and Annapolis Subdistricts (Snyder and Gerdemann, 1968; fig. 1). Some of these ore subdistricts (eg., the Old Lead Belt and Mine La Motte) have some exposure at the surface (the deposits of the Southeast Missouri Barite District and Valles Mines have surficial exposure), but can extend to greater depths, up to a few hundred feet. Other subdistricts (eg., Viburnum Trend and Indian Creek) have no surficial expression, and are several hundred to more than 1,000 ft deep. The Palmer area in Washington County (also called the Shirley-Palmer area, or the Fourche a Courtois Mines) and the Valles Mines (fig 2) also have been included as subdistricts of the Southeast Missouri Lead District in some reports (Snyder and Gerdemann, 1968; Seeger, 2008). This inclusion may be because of a relatively large amount of lead and zinc production or because of non-economic mineralization in the Bonneterre Formation, as is the case at least in the Palmer area (Snyder and Gerdemann, 1968), but because the only mining that has occurred in these areas has been in the residuum and the Potosi Dolomite and younger formations and not the Bonneterre Formation, these mining areas are considered in this report to not be part of the Southeast Missouri Lead District.

Previous Investigations

A large number of publications were reviewed for this report. Cited publications are listed in the "References" section of this report; the more notable publications are described here, in mostly chronological order.

The first known published description of the lead mines of Missouri is a report by Moses Austin, one of the early lead-mine owners in Missouri, on the lead mines of "Upper Louisiana". This report was delivered to the U.S. Congress in 1804 by Amos Stoddard, Captain and First Civil Commandant of Upper Louisiana (Stoddard, 1804). Ten mines are described, some of which are in the Southeast Missouri Barite District (this or any other district term was not in use at that time and would not be for many years). General mining and smelting methods are mentioned, as well as some basic geologic descriptions. The report also provides estimates of the area population and number of workers employed at the mines, as well as production estimates, both in terms of pounds of lead produced and dollar values.

Henry Rowe Schoolcraft traveled through the states and territories west of the Appalachian Mountains and lived for a year in the Missouri Territory where he observed mining practices first hand. Schoolcraft (1819) describes the landscape of the mining area, including its soils and streams, and gives a history of mining up to 1819, including some of the early exploration for gold and silver and the eventual development of lead mining. He lists 45 of the more notable past and present (as of 1819) lead mines, 39 of which were in Washington County and 2 in Jefferson County, gives a general description of the mode of ore occurrence, and describes several mines in detail. He also describes mining and smelting practices, including a detailed description of a log furnace and an ash furnace and a general description of the amount of lead recovery and waste that resulted from each. Production figures for individual mines and the collective production from mines of the area (including some mines from outside the Southeast Missouri Barite District) are estimated, and several recommendations are given for more efficient operations and improved production. Schoolcraft (1819) also notes the occurrence of barite in the ore deposits, though barite was not recovered at that time.

In 1855 George C. Swallow, Missouri State Geologist, delivered the second annual report of the Geological Survey of Missouri to the Missouri Secretary of State (Swallow, 1855). One of the chapters of the report is ”A Preliminary Report of Some of the Principal Mines in Franklin, Jefferson, Washington, St. Francois, and Madison Counties, Missouri”, by Dr. A. Litton, M.D. (Litton, 1855), which includes lead mines inside and outside the Southeast Missouri Barite District. A brief history of lead mining in Missouri is given, which began 135 years earlier in 1720. Descriptions are given for many mines, by county, which generally consist of the public land survey location, a description of ore occurrence, the history and production of the mine, and for several mines a cross section showing individual shafts. The information given for each mine was obtained either by direct observation during a visit, or from a reliable source when direct observation was not possible. A general description of lead furnaces and their operation is given, by county, and several furnaces are described in more detail, including the public land survey location, and historic lead production. No mention of barite mining is made.

A geological survey was conducted of counties along and adjacent to the Southwest Branch of the Pacific Railroad (Swallow, 1859), including the mining areas of the Southeast Missouri Barite District. Brief descriptions of a number of mines in Jefferson County are given, some of which were also given in Litton (1855). A table lists 86 mines in Jefferson and Washington Counties, and 17 furnaces in Jefferson and Washington Counties.

Pulsifer (1888) traces the world history of lead mining, processing and manufacture of white lead (hydrous lead carbonate commonly used as a paint pigment) from antiquity to 1888. Chapters on mining, and smelting and refining in the United States describe the early history of lead mining in Missouri, including the Southeast Missouri Barite District.

Winslow (1894) is the definitive report on lead and zinc mining as of 1894, and is in three parts. Part One gives an overview of world lead and zinc mining, a more detailed description of United States lead and zinc mining, and a chapter by Robertson (1894a) on worldwide industries and production statistics of lead and zinc, including the metallurgy of lead and zinc. This chapter includes details of several types of lead furnaces, including drawings and the history of different furnaces, with improvements in lead recovery and reductions of loss of lead to the environment resulting from improved technology through time. Zinc furnaces are also described. Part Two contains a history of lead mining in Missouri, including but not limited to the Southeast Missouri Barite District and the Valles Mines, with a section on early development (from discovery in about 1720 until 1800), and subsequent sections by one or two decades. The development of different mines throughout Missouri is presented, and mining and metallurgy practices at various mines and some production and employment figures are given. General descriptions of the lead ore deposits of Missouri are given, including the form, mineralogy, structure, and genesis of the ore bodies. Part Two also contains a chapter by Robertson (1894b) describing the lead smelting and manufacturing industries in Missouri in 1894, including a description of the different furnaces in use at the time, and a series of tables giving production statistics by county. Part Three contains detailed geologic descriptions of the more important lead and zinc mines in Missouri, including a section on the “Washington County Subdistrict” (Washington, Jefferson, Crawford, and extreme northern St. Francois Counties) of the “Southeastern District”. These descriptions include plan view maps, cross sections, some photographs, and some individual mine production figures. Barite, which by then had some commercial value, is described as being of such quantity as to be an “object of independent search”.

Ingalls (1908) presents a history of lead and zinc mining and smelting in the United States, up to 1908. A chapter on Missouri describes the history of mining and smelting in Missouri, including mines of the Southeast Missouri Barite District. Descriptions of smelting methods, including production and losses, and drawings of furnaces are given.

Buckley (1908) describes the geology and mines of the “Disseminated Lead Deposits of St. Francois and Washington Counties”. Although the lead deposits of the Southeast Missouri Lead District are the focus of Buckley (1908), he also describes the geology of the barite-lead deposits of the Southeast Missouri Barite District for the purpose of formulating a comprehensive theory of the genesis of southeastern Missouri lead ores. He provides some production figures that demonstrate the growth and prominence of the Southeast Missouri Lead District and the relative decline of the “Washington County Subdistrict”. He describes and locates on an accompanying map 33 “barite diggings” in a portion of the Southeast Missouri Barite District, and by these descriptions indicates that by that time barite had become the resource of interest in the district rather than lead.

Steel (1910) describes the geology, mining, and processing of barite in Washington County. The geology of the deposits is described in some detail, though generally not for individual deposits. The geologic history of Washington County is summarized, and the origin of the barite deposits is hypothesized. Mining methods are described in detail, including the process of digging shafts, drifting from the shafts, and cleaning of the ore at the mine site, and other mining practices are described such as prices paid per ton of ore and payment of royalties. The milling process of one barite mill is described in detail, from raw feed to finished product, and a flow diagram is given.

Hill (1917) gives an account of the barite industry in the United States in 1915, and describes the general geology of barite deposits, mining and processing methods, production by state (Missouri was the largest producer), marketing and prices of barite, several barium products and their manufacturing processes, and the uses of barium products. A list of suppliers of crude barite is given, of which 18 were located in Missouri, and a list of manufacturers of ground barite is given, of which 3 were located in Missouri.

Ball (1916) describes the geology and mining of lead in Washington County in 1916. Mechanized mining was producing large tonnages of lead ore in other parts of Missouri by then, but "mining methods of a century ago prevail" in Washington County in 1916, and these are described, including descriptions of a miner's workday and week, and other aspects of the life of a lead miner at that time. A sketch map of Washington County is given, which shows the location of a large number of lead diggings in Washington County.

Tarr (1918) provides a comprehensive description of the geology of Missouri barite deposits as of 1918, particularly those of the Southeast Missouri Barite District (the Central Missouri Barite

District, a lesser, but still important district, also is described). The general geology of Washington County is given, including stratigraphy, structure, and geologic history, and the economic geology (mineralogy, occurrence, and concentration by weathering) of the barite deposits is described. Different ideas regarding the genesis of the deposits are discussed, and a hypothesis of ore genesis is proposed. Mining and processing methods are described, and a list of 39 uses of barite is given. Tarr (1919) also describes the barite deposits of Missouri in a more condensed report.

Weigel (1929) describes the barite industry in Missouri for both the Southeast Missouri Barite District and the Central Missouri Barite District. The geologic setting and economic geology of each district are described, and the genesis of the ore deposits is discussed. By 1929, mining and processing methods had evolved to include mechanized mining with steam shovels and mechanical washing and concentrating, in addition to continued hand methods, and these are described. The marketing and uses of barite also are described.

Dake (1930) primarily is a report on the stratigraphy, structure, and geologic history of the Potosi and Edgehill 15-minute quadrangles, which are mostly south of Washington County. However, central and south-central Washington County is in the Potosi quadrangle, and because of the importance of barite mining in Washington County in 1930 and the previous importance of lead mining in Washington County, the economic geology of the deposits within the quadrangle are described, including the Palmer, Potosi, and Old Mines areas. A discussion of lines of evidence in support of a theory of descending, rather than ascending waters having deposited the barite and lead is given.

Harness and Barsigian (1946) describe barite mining and marketing throughout the United States, and briefly describe the geology of the barite deposits of southeastern Missouri. Different mining methods and processing employed in different parts of the country in 1946 are described, including Missouri. Previous hand-mining methods are described, and a discussion of legal and economic factors contributing to the decline of hand-mining and the rise of mechanized mining is given. Also described is the process of grinding and bleaching barite, and various uses of barite are described.

The U.S. Bureau of Mines examined the Krueger zinc deposit about 6 miles (mi) west of Potosi, the site of previous lead mining to a depth of about 100 feet (ft; Ballinger, 1946). Twenty-four holes were drilled as deep as 259 ft and intersected either “good” ore or “low-grade” ore in 13 of the holes. Several years later Ligasacchi (1959) studied the Krueger zinc deposit and nearby occurrences of barite in bedrock. Several forms of ore occurrence, including barite in a dolomite breccia matrix, are described and illustrated in photographs.

Cheney (1949) presents an overall description of the barite industry in the Unites States, including the geographic distribution of ore deposits, geology, mining methods, processing, production and uses of barite. He describes the barite industry in the important barite producing states of Arkansas, Georgia, and Missouri, and other states of lesser importance. He describes the geology of the barite deposits of the Southeast Missouri Barite District and summarizes previous authors’ evidence and conclusions regarding the genesis of the ores. The history of barite mining methods in the district is given, from older hand-mining methods to mechanized methods used in 1949, and processing methods in use in 1949 are described, including a flow sheet for two different mining companies.

Thompson (1955) is a series of articles that describe the development of lead mining in southeastern Missouri. Both the Southeast Missouri Barite District and the Southeast Missouri Lead District are covered. Descriptions are given of early exploration for metals in Missouri, mines, and mineral processing, in large part citing previous reports, including Schoolcraft (1819).

Muilenburg (1954) and Muilenburg (1957) provide descriptions of the barite industry in Missouri in the 1950’s. The geology of both the Southeast Missouri Barite District and the Central

Missouri Barite District, and mining and milling practices in the 1950s are described. Some production figures are provided.

Brobst (1958) reviews the history of the barite industry in the United States, the geochemistry of barium, and the mineralogy of barite deposits. He reviews the geology of several districts in different states, including the “Washington County District”. Mining and benefication (processing) methods are briefly described, exploration methods are explained, domestic production and consumption figures are given, and barite resources are described.

A report on the water and mineral resources of Missouri published jointly by the U.S. Geological Survey and the Missouri Division of Geological Survey and Water Resources contains a chapter on barite (Brobst and Wagner, 1967). The history and uses of barite area described, annual production of barite in Missouri since 1900 is given, the geology of the Southeast Missouri Barite District is described, and projections of barite reserves and future production are given. Another chapter in the same report describes the lead and zinc industry in Missouri (Kiilsgaard, Hayes, and Heyl, 1967). The history and production of lead mining in Missouri is described, and although much of the chapter discusses the large lead districts in Missouri, the history, production, and geology of the Potosi-Palmer mining area in Washington County and the Valles Mines in Jefferson and St. Francois Counties are briefly described.

In a publication prepared for the 200th anniversary commemoration of the city of Potosi, Showater (1963) traces the history of lead and barite mining in southeastern Missouri, with an emphasis on mining in the Potosi area. Profiles of several historical figures important to mining in the Potosi area are given. Mining methods are described, and descriptions of the life of a miner are given.

Snyder (1968a) briefly describes different types of mineral deposits throughout the midcontinent United States. He provides separate discussions of the “Southeast Missouri Barite-Lead Deposits” and the Southeast Missouri Lead District, and provides criteria for defining each and distinguishing one from the other. Results of 7 lead isotope analyses from the Southeast Missouri Barite District are summarized; galena from the district is described as overlapping but being slightly more radiogenic than galena from the “Lead Belt” (Old Lead Belt Subdistrict of the Southeast Missouri Lead District).

Wharton (1972) made an inventory of barite tailings ponds, mostly in Washington County, for the purpose of determining tonnage and grade of potential barite reserves in the ponds. Four ponds were drilled and core samples were collected and analyzed for barium concentrations using X-ray fluorescence spectrometry. The lead content of the tailing ponds was not reported. Metallurgical tests were run to determine barite grain size. A map showing the location of 67 inventoried tailings ponds is given, and detailed maps and cross section are given for each of the 4 ponds that were drilled showing locations of drill holes, barite grade and thickness at each drill location, and areas of different grades of barite in each pond. The report also briefly describes the geology of the district, the history of mining and milling methods and current (1972) methods, and discusses mill recovery and losses.

Wagner (1973) is an important contribution to the understanding of the geology of the Southeast Missouri Barite District. The study area was a large part of the district, about 160 square miles (mi^2), but did not include some mining areas such as the Richwoods area in northeastern Washington County, the Palmer area in southwestern Washington County, and the Valles Mines area in southern Jefferson and northern St. Francois Counties (fig. 2). Barite-lead deposits were examined in detail both in the field and in the laboratory (thin and polished sections were studied, and X-ray diffraction tests were done) for the purpose of understanding the nature of the ore deposits, including the mineralogy of the deposits and their occurrence in the residuum and in bedrock, the stratigraphic and structural controls on mineralization, and to develop a genetic model for the district. Research focused on the original sedimentary lithologies and their influence on mineralization, particularly algal stromatolites, the relation of the deposits to geologic structure, including faults, different types of barite mineralization and their relation to other mineralization, including lead mineralization, wall rock alteration, the relation between ore minerals and drusy quartz in the Potosi Dolomite, mineral and textural zoning of the deposits, mineral paragenesis, fluid inclusions, bedrock mercury anomalies, and the physical and chemical controls on mineralization that help explain the environment of deposition and genesis of the deposits. A detailed stratigraphic section and several maps of the study area are included: a geologic map, a map of trends of fractures and faults, maps showing joint patterns along Mill Creek and Mine a Breton Creek, a map of barite mines and tailings ponds in 1973, and a barite deposit textural-zoning map. This was summarized several years later in Kaiser and others (1987; Wagner was a second author), who also used more recent sulfur and oxygen isotope data to interpret the genesis of the barite-lead deposits.

Burford (1978) summarizes the history of mining in Missouri from the earliest explorer days until 1978. Although many resources are described, including barite, particular attention is given to lead because of its importance to the economy of Missouri for many years. The history of lead mining throughout Missouri is given, beginning with settlers in southeastern Missouri in the early 1700’s.

Wharton (1986) summarizes the development of barite mining in Washington County and current (1986) mining and processing methods; this was toward the end of the period of barite mining. A brief history of geologic investigations of the deposits also is given.

Park (2006) provides descriptions of many abandoned mines in Missouri, including mines in the Southeast Missouri Barite District and Valles Mines. The descriptions are presented in the form of a travel guide for exploring old mining areas in Missouri, with brief, but in some cases detailed accounts of mining areas and individual mines, mining methods, production data, and descriptions of historical mining figures. Maps are included in the form of sketch location maps showing old mines and furnaces.

More emphasis is given to lead mines than barite mines. A historical account of the development of mining in Missouri also is given.

Although Seeger (2008) focuses attention on the mine facilities and environmental effects of mining in the Viburnum Trend, the early history of lead mining in Washington County is briefly presented. As mentioned in “Description of the Study Area”, Seeger (2008) and Snyder and Gerdemann (1968) regard the Shirley-Palmer area and the Valles Mines (fig. 2) as subdistricts of the Southeast Missouri Lead District, along with the Viburnum Trend and other subdistricts. The Shirley-Palmer area and the Valles Mines, however, as stated in “Definition of the Southeast Missouri Barite District and the Valles Mines”, are not included in the Southeast Missouri Lead District for this report.

Blount (ca. 1950) is a compilation of video clips of barite mining from what is reported to be the 1930’s. This compilation, which may have been produced about 1950, has no audio but contains grainy black and white video clips of both hand mining and processing of barite and early mechanized barite strip mining and processing. Wood (1963) is a grainy color video showing mechanized strip mining of barite and a barite processing plant.

The Missouri Geological Survey (MGS) compiled for the Missouri Department of Natural Resources Division of Environmental Quality a Mined Lands Geographic Information System (GIS) shapefile showing locations of barite strip mines and tailings ponds (Cheryl Seeger, Missouri Geological Survey, written communication, October 27, 2015). The MGS also maintains an Inventory of Mines, Occurrences, and Prospects (IMOP; Missouri Department of Natural Resources, 2015a). The following description of the IMOP database is mostly from Cheryl Seeger (Missouri Geological Survey, written commun., June 14, 2016): The IMOP database contains information, including location data, for all mineral resource types (lead, coal, limestone, etc.) in Missouri, categorized as mines (active or past producer), occurrences, and prospects. The database is based on the original U.S. Bureau of Mines

Mineral Industry Location System database; however the database and data have been extensively updated, additional field have been added and more than 11,000 additional sites have been added. The IMOP database is continually being revised and additional mines sites being added. Data were compiled by the MGS from historical references, from in-house unpublished documents, correspondence, maps and field notes unavailable elsewhere, as well as from topographic and geologic maps, Digital Orthophoto Quarter Quads and aerial photographs. This database has location and other data, including some brief descriptions of barite and lead mines, occurrences and prospects in the Southeast Missouri Barite District and Valles Mines, and references for the information in the database.

Geology of the Southeast Missouri Barite District and the Valles Mines

The geology of the Southeast Missouri Barite District, and to a lesser extent the Valles Mines, has been described in several reports, the earliest of which focus on lead, and the latter of which focus on barite. The geology is the same, as the two resources commonly occur together, and the changing focus is a reflection of the changing economic importance of the two resources. The first comprehensive reports on the geology of the study areas were Winslow (1894) and later Buckley (1908), both of which describe the mining areas as a lead district. The first report on the geology that treats the mining areas as a barite district is Steel (1908); followed by the more detailed geologic descriptions given in Tarr (1918), Tarr (1919), and Dake (1930). More recently, Wagner (1973) and Kaiser and others (1987) also describe the Southeast Missouri Barite District as a barite district, and provide the most complete geologic descriptions available. These and some other reports (e.g., Dake [1930]) focus on areas smaller than the district, but are applicable to the entire district.

General Geologic Setting

The study area is located within the Salem Plateau of the Ozarks Plateaus Physiographic Province (Fenneman, 1938), also referred to simply as the Ozarks. The Salem Plateau is a large area in southern Missouri and northern Arkansas composed of Cambrian- and Ordovician-age sedimentary rocks that have been uplifted and dissected by erosion. The topography of the study area is one of rolling hills with incised valleys, and is partially wooded. The Big River and its tributaries drain eastern Washington County, western Jefferson County, and northwestern St. Francois County (fig. 2). Western Washington County is drained by tributaries of the Meramec River, and northeastern St. Francois County and eastern Jefferson County are drained by tributaries of the Mississippi River.

Structure

The Ozarks Plateaus Physiographic Province is the physiographic expression of the Ozark Dome, one of several domes and arches which, with intracratonic basins, define the structural framework of the United States midcontinent. The core of the Ozark Dome is the St. Francois Mountains in southeastern Missouri, an area of exposed Precambrian-age rocks which also underlay basal Paleozoic sedimentary rocks throughout the Ozarks (fig. 3). Following an extensive period of igneous activity, the Precambrian-age rocks were subject to a long period of erosion which produced a rugged topography with up to 2,000 ft of relief in the St. Francois Mountains (Thacker and Anderson, 1977). The area slowly subsided during Late Cambrian and Early Ordovician time (Snyder, 1968b) during which the Precambrian terrain stood as an island complex surrounded by a dominantly transgressive shallow sea. Sediments filled valleys and covered all but the highest hills. Later, tectonic uplift resulted in widespread erosion followed by subsidence and deposition of more sediment. This sequence of uplift followed by erosion, subsidence and sedimentation occurred repeatedly throughout the Paleozoic until the end of the Pennsylvanian period (Snyder, 1968b) when the Ozark dome became a positive feature for the last time.

Bedrock formations generally dip gently away from the St. Francois Mountains, and erosion has resulted in an outcrop pattern of progressively younger formations away from the St. Francois Mountains. The Southeast Missouri Barite District and the Valles Mines are north of the St. Francois Mountains, and the study area displays this outcrop pattern in a general way, with bedrock formations becoming younger toward the northwest, north, and northeast, away from the igneous core of the St. Francois Mountains (fig 4). This outcrop pattern is not simple, however, as numerous faults occur, offsetting geologic formations and juxtaposing formations of different ages across faults. Although some areas are more faulted than others, the greater density of faults in the northern part of Washington County and in southern Jefferson and northern St. Francois Counties, shown in figure 4, is the result of more detailed geologic mapping at 1:24,000 scale in these areas. The geology shown in figure 4 is from the Missouri Department of Natural Resources (2015b) and reproduces the geology shown in the Geologic Map of Missouri (Missouri Department of Natural Resources, 2003). The geologic structures shown in figure 4 also are from the Missouri Department of Natural Resources (2015b), and are revised slightly from what are shown in the Geologic Map of Missouri.

Figure 4. Geologic map of the study area and vicinity

Most of the ore deposits in the study area occur in a structural block bounded by three fault systems, or occur in the fault systems themselves: the Palmer fault system to the southwest, the Big River fault system to the southeast, and the Vineland fault system to the northeast (fig. 4; Wagner, 1973). The Palmer and Vineland fault systems are not single continuous faults, but instead are systems of subparallel faults, and many of the ore deposits occur within the faulted areas. The Palmer fault system trends northwest-southeast in southern Washington County and changes to trend east-west in southwestern Washington County and in Crawford County, and consists of subparallel high-angle normal faults with a total of 200 to 1,200 ft of downward displacement to the northwest or north (McCracken, 1971). The Vineland fault system is sometimes called the Valles Mines-Vineland fault zone, and is regarded as a northwest extension of the Ste. Genevieve fault system (McCracken, 1971; Nelson and Lumm, 1985). The northwest-trending Vineland fault system is a zone of high-angle normal faults with downward displacement to the northeast of as much as 800 ft (McCracken, 1971). The northeast-trending Big River fault system is a high-angle normal fault or set of en echelon faults with up to 120 ft of downward displacement to the northwest, and is regarded as a southwest branch of the Ste. Genevieve fault system (McCracken, 1971).

Other named faults occur in the study area besides the three bounding fault systems. The Berryman fault (fig 4) extends northwest from the Palmer fault system and has a downward displacement to the southwest (McCracken, 1971). The Shirley fault zone trends northwest (fig 4) and consists of several faults with about 300 ft of step-down displacement to the southwest (McCracken, 1971). Wagner (1973) describes the Mineral Point fault system, the Fertile-Cruise Mill fault system, and the Racola fault (not labeled on figure 4) and other unnamed faults and fault systems. Near-vertical joints commonly form two joint sets approximately perpendicular to each other, and sometimes a third and less commonly a fourth joint set are present (Wagner, 1973).

Wagner (1973) and Kaiser and others (1987) recognized a structural pattern, or structural "grain" in the Southeast Missouri Barite District. This structural grain is defined by faults and joints that trend northwest-southeast in the northwestern part of the district and east-west in the southeastern part of the district (Kaiser and others, 1987). The greatest displacement within the structural block is on the peripheral faults (Palmer and Vineland fault systems), with less displacement along the faults in the interior of the structural block (Fertile-Cruise Mill fault system, Shirley fault zone, Mineral Point fault system), and these faults form horst and graben structures (Wagner, 1973). More details regarding the geologic structure of the Southeast Missouri Barite District, the relation of district structure to regional structural patterns, and possible stress patterns that produced these geologic structures, including tensional stresses responsible for the horst and graben structures, are found in Wagner (1973).

Stratigraphy

The Precambrian basement in southeastern Missouri consists of rhyolitic porphyries intruded by granites and diabase dikes and sills (Snyder and Gerdemann, 1968; Missouri Department of Natural Resources, 2003; fig. 3). Precambrian-age rocks are exposed in the study area in southeastern Washington County and to a lesser extent in west-central Washington County. There is more exposure of Precambrian-age rocks in the St. Francois Mountains south and southeast of Washington County (fig. 4).

The Cambrian-age Lamotte Sandstone (fig. 3) is the oldest Paleozoic formation in southeastern Missouri. It is predominantly a quartzose sandstone but is locally arkosic or conglomeratic, and can contain siltstone or dolomite beds (Snyder and Gerdemann, 1968; Thompson, 1995; Thompson and others, 2013). It occurs in the subsurface throughout most of the study area, and is exposed in a small area in southeastern Washington County. The Lamotte Sandstone varies in thickness from zero where it pinches out against Precambrian knobs to about 500 ft in areas of the St. Francois Mountains (Thompson, 1995). An isopach map of the Lamotte Sandstone (Thacker and Anderson, 1979) covers the approximately southern two-thirds of Washington County, and the Lamotte Sandstone has a maximum thickness of about 350 ft in this area. The Lamotte Sandstone locally contains lead-zinc ore in southeastern Missouri, and was mined at the Mine La Motte, Indian Creek, and to a lesser extent Old Lead Belt Subdistricts of the Southeast Missouri Lead District (fig 3).

The Cambrian-age Bonneterre Formation (fig. 4) overlies the Lamotte Sandstone. It is predominantly dolomite in the mining areas of southeastern Missouri (Snyder and Gerdemann, 1968), and contains some shale beds. An isopach map of the southern two-thirds of Washington County (Thacker and Anderson, 1979a) shows that its thickness ranges from zero to about 400 ft in this area and that it is exposed in parts of southeastern Washington County. The outcrop area of the Bonneterre Formation is not shown in figure 4; instead, figure 4 shows the outcrop area of the combined Bonneterre Formation and overlying Elvins Group (fig. 3). The Bonneterre Formation is the host rock for the lead-zinc deposits of the Viburnum Trend, Old Lead Belt, Irondale, and Annapolis Subdistricts of the Southeast Missouri Lead District, and is also mineralized at the Indian Creek and Mine La Motte Subdistricts where the Lamotte Sandstone is the main ore host.

The Cambrian-age Elvins Group (fig. 3) consists of two formations: the Davis Formation and the overlying Derby-Doerun Dolomite. The Elvins Group is exposed in small areas in southeastern Washington County, northern St. Francois County, and along the Big River and its tributaries in northeastern Washington County and southwestern Jefferson County. An isopach map of the southern two-thirds of Washington County (Thacker and Anderson, 1979c) shows that its thickness ranges from zero to about 300 ft thick in this area; it thickens to about 450 ft thick in northwestern Washington County and central Jefferson County (Imes, 1990). The Davis Formation conformably overlies the Bonneterre Formation, and is composed of interbedded shale, dolomitic limestone, siltstone, and sandstone (Snyder and Gerdemann, 1968; Wagner, 1973). An isopach map of the southern two-thirds of Washington County (Thacker and Anderson, 1979b) shows that the Davis Formation thickness ranges from zero to about 180 ft in this area; Wagner (1973) states that the average thickness is 165 ft in the

Southeast Missouri Barite District. The Davis Formation is conformably overlain by the Derby-Doerun Dolomite which consists of two units: a lower, argillaceous dolomite and an upper, massive oolitic or algal-reef dolomite (Snyder and Gerdemann, 1968). An isopach map of the southern two-thirds of Washington County (Thacker and Anderson, 1979c) shows that the Derby-Doerun Dolomite thickness ranges from zero to about 150 ft in this area. The Elvins Group generally has low permeability compared to formations above and below it, and is considered a regional confining unit (St. Francois confining unit) by the U.S. Geological Survey (Imes and Emmett, 1994).

The Cambrian-age Potosi Dolomite (fig. 3) conformably overlies the Derby-Doerun Dolomite. The Potosi Dolomite is the most important formation in the Southeast Missouri Barite District and the Valles Mines because the residual soil (residuum) derived from it hosts most of the barite and lead in the Southeast Missouri Barite District, and ore also is found in the formation, particularly at the Valles Mines. The Potosi Dolomite is exposed in a large part of the study area. The bedrock geologic map of the study area (fig. 4), however, shows the Potosi Dolomite and Eminence Dolomite as a single mapped unit because the source of the mapping for figure 4 (Missouri Department of Natural Resources (2015b) groups the two formations as a single mapped unit. Recent revisions to the Cambrian stratigraphy in Missouri (Thompson and others, 2013) name the “Potosi-Eminence Dolomite” as a formal rock unit in addition to the Potosi Dolomite and the Eminence Dolomite, recognizing the difficulty in picking the contact between these two formations in some areas. Geologic maps at a 1:24,000 scale are available (Missouri Department of Natural Resources, 2015b) for northeastern Washington County and for Jefferson County, and although these maps show the Potosi and Eminence Dolomites as two separate mapped units, they are not reproduced in this report because the mapped area does not cover a large part of the Southeast Missouri Barite District. Wagner (1973) contains a geologic map that shows the two formations as separate units, but this map is not reproduced for this report because his study area also covers only a portion of the Southeast Missouri Barite District. Wagner (1973) states that the Potosi Dolomite is exposed in the major valleys and lower hills in about 50 percent of his study area, ranges from about 215 to about 390 ft thick, and appears to thin to the north. Thacker and Anderson's (1979d) isopach map of the southern two-thirds of Washington County show that the Potosi Dolomite ranges in thickness from zero to about 375 ft. Generally, the Potosi Dolomite is a medium crystalline, massive bedded dolomite with abundant quartz druse that is associated with chalcedony and chert (Wagner, 1973; Thompson, 1995; Thompson and others, 2013). Because of the importance of the Potosi Dolomite in the Southeast Missouri Barite District, Wagner (1973) describes the Potosi Dolomite in detail, including descriptions of three lithologic types (calcarenite, algal-stromatolite biostrome, and carbonate muds), diagenesis, including the development of drusy quartz, weathering characteristics, and the relation between lithologic characteristics and ore deposits.

The Cambrian-age Eminence Dolomite (fig. 3) conformably overlies the Potosi Dolomite, and is the second most important ore-bearing formation in the Southeast Missouri Barite District, after the Potosi Dolomite. It is exposed in much of the study area, and is combined with the underlying Potosi Dolomite as a single mapped bedrock unit in figure 4. Wagner (1973) estimates that it is exposed in about 35 percent of his study area and that it varies from about 120 to 195 ft thick. Thacker and Anderson (1979d) estimate that it ranges in thickness from zero to about 250 ft in the southern two-thirds of Washington County, and that the formation thins to the north. Generally, the Eminence Dolomite is a medium to massive bedded, medium to coarsely crystalline dolomite with small amounts of chert (mostly in the upper half of the formation), small amounts of quartz druse, and locally thin green clay seams (Wagner, 1973; Thompson, 1995;Thompson and others, 2013). Because of the importance of the Eminence Dolomite in the district, Wagner (1973) describes the Eminence Dolomite in detail, including descriptions of five lithologic types (calcarenite, algal-stromatolite biostrome, carbonate muds, green clay seams, and a recrystallized dolomite without recognizable structure that makes up about 75 percent of the formation, termed "cryptalgal" lithology), diagenesis of these lithologies, weathering characteristics, and the relation between lithologic characteristics and ore deposits.

The Gasconade Dolomite (fig. 3) is the oldest Ordovician-age formation in Missouri. Thompson (1995) states that the Cambrian-Ordovician contact is conformable in parts of Missouri and unconformable elsewhere in Missouri; Wagner (1973) states that an unconformity marks this contact in his study area, but that the unconformity is inconspicuous. The Gasconade Dolomite is exposed in a large part of western and northwestern Washington County, and small parts of southwestern and southeastern Jefferson County; in some places this is the result of faulting that has down-dropped the Gasconade Dolomite relative to adjacent Cambrian formations (fig 4). Wagner (1973) states that it is the bedrock formation in about 10 percent of his study area, where it is present on most of the higher ridges, and that it is about 220 ft thick in the district. The Gasconade Dolomite is mostly medium to coarsely crystalline dolomite with abundant chert. Thompson (1995) divides the formation into three units: the upper Gasconade, which contains relatively small amounts of chert, the lower Gasconade, which may be up to 50 percent chert, and beneath that a basal unit called the Gunter Sandstone Member, which varies regionally from sandstone up to about 30 ft thick, to a sandy dolomite. Wagner (1973) describes the Gunter Sandstone Member in his study area as coarsely crystalline dolomite interbedded with finely crystalline argillaceous dolomite with scattered sand grains. A small number of ore deposits occur in the Gasconade Dolomite in the Southeast Missouri Barite District and in adjacent counties.

The Ordovician-age Roubidoux Formation (fig. 3) overlies the Gasconade Dolomite; the contact is conformable in Wagner's (1973) study area. The formation consists of cherty dolomite sandy dolomite dolomitic sandstone, and sandstone (Thompson, 1995). The Roubidoux Formation is exposed in parts of western and northwestern Washington County, and small parts of southwestern and southeastern Jefferson County; in some places this is the result of faulting that has down-dropped the Roubidoux Formation relative to other formations (fig. 4). A small number of ore deposits occur in the Roubidoux Formation in the Southeast Missouri Barite District and in adjacent counties.

The Ordovician-age Jefferson City Dolomite and the overlying Ordovician-age Cotter Dolomite (fig. 3) are mapped together as a single unit on figure 4 and are exposed in a large part of Jefferson County on the northeast, down-dropped side of the Vineland fault system. The Jefferson City Dolomite is predominantly medium to finely crystalline dolomite and argillaceous dolomite (Thompson, 1995). The Cotter Dolomite is predominantly medium- to finely-crystalline cherty dolomite (Thompson, 1995). A small number of ore deposits of the Southeast Missouri Barite District occur in the in the Jefferson City and Cotter Dolomites. Younger Ordovician-age, Devonian-age, and Mississippian-age formations form the bedrock in northern and southeastern Jefferson County (figs. 3 and 4).

Clayey residuum overlies carbonate formations in Missouri, including the Cambrian- and Ordovician-age formations in the study area. The residuum is the insoluble residue that remains from the chemical removal of the soluble carbonate minerals of the formations as part of the weathering process. Residuum is mostly clay, but also contains chert, sand and sandstone, and drusy quartz and chalcedony, particularly where the residuum is developed from the Potosi Dolomite. The bedrock surface is sometimes “pinnacled”, that is, the surface is irregular because of weathering along fractures. Early miners noted that the bedrock surface sometimes was soft and friable and called this “sand rock”; this was not quartz sand but instead was loosely consolidated dolomite rhombohedrons resulting from the solution and recrystallization of the dolomite bedrock (Muilenburg, 1957; Tarr, 1918).

Economic Geology of the Ore Deposits

The economic geology of an ore district is a description of the various characteristics of the ore deposits, such as ore and gangue mineralogy and paragenesis, occurrence, zoning, and the structural and stratigraphic controls of mineralization, and how they act together to affect ore deposition. These characteristics, including their variability, not only describe an ore district or subdistrict, but also lead to hypotheses of the genesis of the ore deposits. Whereas these characteristics have genetic implications, ore genesis of the Southeast Missouri Barite District and the Valles Mines is beyond the scope of this report.

Mineralogy and Paragenesis

Minerals of an ore deposit are described as primary, which are minerals deposited by the ore fluids, and secondary, which are minerals that form later as an alteration of the primary minerals as a result of a change in environmental conditions, such as a change to an oxidizing and lower temperature environment. Primary minerals are commonly described as hypogene, meaning they were deposited by warm ascending ore fluids; secondary minerals are commonly supergene, meaning they are formed by cooler, descending fluids. Minerals are further described as ore minerals, which are recovered for their economic value, and gangue minerals which have no economic value.

Barite (barium sulfate) is a primary ore mineral; however some barite is secondary (Wagner, 1973). The primary, and most important lead ore mineral, is galena (lead sulfide). Secondary lead minerals are cerussite (lead carbonate; also called “dry bone” by the early miners), and anglesite (lead sulfate). These secondary lead minerals commonly occur as alteration products of galena, although they may not be described for all deposits. They were locally important ore minerals, despite being discarded during the early lead-mining years before their value was realized (Litton, 1855). The primary zinc ore mineral is sphalerite (zinc sulfide); smithsonite (zinc carbonate) is a secondary mineral that also was mined as an ore mineral, and was more important than sphalerite in some deposits, including the Valles Mines (Kiilsgaard and others, 1967). Chalcopyrite (copper-iron sulfide) also occurs in the ore deposits as a primary mineral; the IMOP database indicates that copper was recovered as the primary resource in a few mines (chalcopyrite was also mined in some deposits in the nearby Franklin County Mines; fig. 1).

Some gangue minerals were pre ore-stage, that is, they were deposited before ore mineralization: these include the silica minerals (quartz, chalcedony, and chert), possibly marcasite (iron sulfide), and some dolomite (calcium-magnesium carbonate; Wagner, 1973; Kaiser and others, 1987). Primary gangue minerals are dolomite and pyrite (iron sulfide). Secondary gangue minerals are malachite (copper carbonate), aurichalcite (copper-zinc carbonate), melanterite (iron sulfate), gypsum (calcium sulfate), limonite (hydrous iron oxide), and jarosite (potassium-iron hydrous sulfate) (Wagner, 1973).

The general order (paragenesis) of ore-stage mineralization is pyrite; galena and sphalerite; white barite; chalcopyrite (rare to minor); clear barite; and calcite (rare to minor) (Kaiser and others, 1987; Wagner, 1973; Tarr, 1918). Not all minerals are present at all locations, and overlapping periods of deposition of minerals was common. For example, most of the sulfide mineralization pre-dates barite mineralization, but small amounts of sulfides were deposited throughout the period of barite deposition (Kaiser and others, 1987). The sulfide minerals are, in decreasing order of abundance: pyrite, galena, sphalerite, and chalcopyrite (Wagner, 1973). Alteration of minerals to secondary minerals occurred after ore-stage mineralization.

Ore Occurrence

Ore deposits of the Southeast Missouri Barite District occur mostly in the clayey residuum overlying bedrock and to a lesser extent in bedrock beneath the residuum. The largest number of deposits occur in the residuum overlying the Potosi Dolomite, followed in importance by residuum overlying the Eminence Dolomite. A lesser amount of ore occurs in the residuum overlying younger formations and in these formations: the Gasconade Dolomite, Roubidoux Formation, Jefferson City Dolomite and Cotter Dolomite. In addition to mineralogical differences, the ore deposits of the Valles Mines differ from the ore deposits of the Southeast Missouri Barite District by occurring more in the bedrock and less in the overlying residuum (Cheryl Seeger, Missouri Geological Survey, oral commun., July 7, 2016). The Cambrian Potosi and Eminence Dolomites are the bedrock formations in the Valles Mines area. Outside the study area, the Gasconade Dolomite and Roubidoux Formation host the ore deposits of the Franklin County Mines (fig. 1). To illustrate the relation between bedrock formations and ore mineralization, figure 5 shows sites of ore mineralization in the study area and three areas of bedrock: areas underlain by the combined Cambrian Potosi and Eminence Dolomites, areas underlain by formations older than the Potosi Dolomite, and areas underlain by formations younger than the Eminence Dolomite. Sites of mineralization are from the MGS IMOP database. All resources (lead, zinc, barite, mixed barite and lead, etc.) are grouped together, and two types of sites are shown: mines; and prospects and occurrences grouped. Although the information for some sites may be limited and some sites may not be located as precisely as others because of the age or quality of the reference for the site (which may be as old as the early 1800's), or because of conflicting location data from different sources, figure 5 serves to illustrate the widespread nature of barite, lead, and zinc mineralization in the study area, and that most mineralization occurs where the bedrock formation is the Potosi Dolomite or

Eminence Dolomite. Also, the stratigraphic column in figure 3 describes the relative amounts of ore in the different formations in the study area and vicinity, including the Southeast Missouri Lead District.

Figure 5. Map of the study area showing the relation of Southeast Missouri Barite District and Valles Mines ore mineralization to bedrock geology, and locations in the study area of ore deposits of the Southeast Missouri Lead District.

It is common for barite and lead to occur together in the Southeast Missouri Barite District; the extent to which they occur together is characterized differently by different authors. Winslow (1894), describing lead mines at a time when barite also was mined, states that the quantity of barite associated with galena was such that it often was an object of independent search. Dake (1930), also describing lead mines, states that barite was an “almost universal accompaniment”. Tarr (1918), describing barite deposits, states that while some barite diggings do not contain any galena, most contain at least a specimen of galena, and that the major part of the district is covered by old abandoned holes of the lead mines (diggings). Kaiser and others (1987) state that minor amounts of sulfides accompany barite, and Wagner (1973) states that galena and sphalerite tend to occur together and are more restricted in aerial distribution than barite. Rueff (2003) shows generalized areas where barite and lead mining occurred; although the two areas overlap to a large extent, the area of lead mining is about twice the size of the area of barite mining, and a large part of southern Washington County is shown as having had lead mining only. Barite, though present, was a not an important resource at the Valles Mines, where zinc was the most important resource (Cheryl Seeger, Missouri Geological Survey, oral commun., July 7, 2016).

A more detailed depiction of barite and lead distribution in the study using the MGS IMOP database is shown in figure 6. Four categories of ore mineralization are shown: barite only, without lead, zinc, or copper; lead or less commonly zinc, sometimes together or with other metals such as copper or nickel, but not with barite; lead or zinc with barite, and in some cases with these other metals; and a few occurrences of iron, with or without lead, zinc, or barite, including the Pea Ridge iron mine. These four categories are simplified from the many groupings of resources in the IMOP database, such as lead, zinc, lead with zinc, zinc with lead, lead with copper, barite, barite with lead, lead with barite, and many other combinations, including some with other metals. Also, some resources are listed in the IMOP database as questionable, for example, “Barium; Lead?”, which means that barium (meaning barite) is present and lead was strongly suggested by sources, but not definitively specified (Cheryl Seeger, Missouri Geological Survey, oral commun., August 13, 2014). This is simplified herein to “barite and lead” with the query dropped. For simplicity of illustration, one symbol is used in figure 6 for mines, occurrences, and prospects. Figure 6 shows that while barite and lead commonly occur together or in close proximity to each other, there are areas where mostly lead is reported or, conversely, where mostly barite is reported. However, there may be sites where only the principal resource was listed by the IMOP data source and not accessory resources which might have been present in only minor amounts; that is, some of the sites shown as a barite-only site may also have lead present, and the same for sites shown as lead-only. Lead mines may be under-represented in the area due to the age of the mining and lack of documentation of specific sites during early mining.

Figure 6. Map of the study area showing the distribution and types of Southeast Missouri Barite District and Valles Mines ore mineralization, and locations in the study area of ore deposits of the Southeast Missouri Lead District

Most of the Southeast Missouri Barite District production was from the residuum, although these deposits commonly extended deeper into the bedrock. In contrast, most of the production from the

Valles Mines came from bedrock mining and not from the residuum (Cheryl Seeger, Missouri Geological Survey, oral commun., July 7, 2016). Descriptions of ore in bedrock (“lode” deposits) by different authors were mostly for the purpose of describing ore occurrences in lead mines (or zinc, especially in the case of the Valles Mines), as barite was never the focus of bedrock mining. Although barite occurs in bedrock with lead and zinc, mining of barite only extended into bedrock when there was enough lead or zinc ore to justify the expense, barite being a by-product (Tarr, 1918).

Most of the ore of the Southeast Missouri Barite District that occurs in bedrock is one of two types of ore occurrence: a) “runs”, or “channels” described by Dake (1930), and also described by Buckley (1908) and Ball (1919) using different terminology, and b) vertical “crevice” ore described by Ball (1916), and also described by Buckley (1908), Dake (1930), Weigel (1929), and Tarr (1918) using different terminology. Ore in bedrock at the Valles Mines appears to be similar to ore in bedrock in the Southeast Missouri Barite District, except for mineralogy. Winslow (1894) describes ore occurrences in bedrock at several mines of the Valles Mines.

The “runs”, or “channels”, described by Dake (1930) are deposits with a greater horizontal than vertical extent, with the vertical extent ranging from a foot to 5 or 6 ft, and sometimes occurring in different levels. He states that these were solution channels, sometimes called caves, that were rarely entirely filled, and were presumably controlled by intersecting joints. He states that most of the ore was this type. Buckley (1908) and Ball (1916) describe these deposits as “pipes” or “pipe” veins. Ball (1916) states that these are semi-cylindrical in form, follow horizontal bedding planes, and are 3 to 8-ft wide and average 6-inches (in) thick. The semi-cylindrical form is the result of ore occurring at the intersection of a joint and a “favorable” bed (Ball, 1916). Minor pipes can lead off of main pipes at or close to a right angle, and systems of pipe veins can occur at several horizons. Winslow (1894) also uses the term “channel” to describe similar horizontally-aligned ore deposits at the Valles Mines. Killsgaard and others (1967) state that these deposits are relatively flat lying but thin, and extend over a large horizontal area.

The vertical “crevice” ore described by Ball (1916) are vertical, tabular deposits that pinch out with depth and form along joints. Cross-veinlets of ore form along secondary joints and cross the main joint at right angles; east-west and north-south crevices are the most common, and can occur as sets along parallel joints. Buckley (1908) describes these as vertical “channels” (using the term “channel” differently than Dake [1930]) with a greater vertical than horizontal extent. Buckley (1908) states that the upper 100 to 150 ft of bedrock, particularly the Potosi Dolomite, was characterized by channels and other openings; the depth of mining, however, is reported to locally have been as deep as 250 ft, with barite occurring with galena (Tarr, 1918). This mode of occurrence is probably what Dake (1930) describes as “fissures” that are traceable for a half mile or more, but are less important than the “channel” ore he describes. The vertical crevice deposits are probably what Weigel (1929) and Tarr (1918) describe as barite in veins; Tarr (1918) states that the majority of veins strike north-south. Winslow (1894) described vertical “chimneys” of ore at the Valles Mines.

Ball (1916) also describes breccia-filling ore, which are vertical tabular masses of ore cementing either fault or solution breccia. Tarr (1918) also states that barite cements breccia. Ore in bedrock is mostly open-space filling (Kaiser and others, 1987) and less commonly replacement of the host dolomite (Buckley, 1908). In addition to the open-space mineralization in channels, crevices and breccia, some disseminated mineralization occurs in the host dolomite. Tarr (1918) describes small masses of barite up to about 2-in in size that fill vugs in the dolomite or replace it, and states that this is more abundant near the veins, showing a genetic relation to the veins. Some of this may be what Kaiser and others (1987) refer to when describing a preference for barite to fill vugs along stromatolite structures in the dolomite.

Because galena, sphalerite, and barite are less soluble than dolomite, chemical weathering of the dolomite bedrock resulted in the concentration of ore minerals in the residuum, and most of the barite and lead mining was in the residuum. Some, particularly early studies, for example Buckley (1908) and Dake (1930), suggested that there was not enough ore in the bedrock to account for the ore in the residuum and that the ore was therefore deposited by descending groundwater. At that time, exposures of the bedrock were limited to natural outcroppings along streams, the bottom of barite and lead shafts in the residuum (many of which had been filled and were not accessible for study), and the small, relative to shafts in the residuum, number of lead mines in bedrock (many of which also were not accessible). Later strip mining of the residuum for barite resulted in better exposures of the bedrock surface and more observation of ore minerals in the bedrock, which has been judged to be abundant enough to account for the ore in the residuum (Wharton, 1986).

Various estimates of the thickness of the ore-bearing residuum have been made. Muilenburg (1957) estimated that the residuum ranges in thickness from a few inches to 40 or 50 ft, with an average of 10 to 15 ft. Weigel (1929), describing the geology of barite deposits, states that the richest barite is found on gentle slopes rather than at the top of hills, and that barite is seldom found in valleys. Barite and lead concentrations can occur randomly distributed in the clay residuum or evenly distributed from top to bottom, but usually the richest ore was found at the bottom of the residuum near the bedrock surface (Muilenburg, 1957; Dake, 1930). Early miners recognized rich “runs” or “leads” of irregular shape and extent alternating with less rich or barren ground. This has been interpreted, for example by Muilenburg (1957), as representing original concentrations in fractures or solution channels – removal of the dolomite by solution left the relatively insoluble ore in roughly the same position as it was in the dolomite. Hillside creep and slumping further distributed the ore over a somewhat wider area. Mechanical removal and distribution of ore minerals by erosion of the residuum is evidenced by the fact that some placer galena was recovered from streambeds in the early days of mining (Ball, 1916; Stoddard, 1804).

Drusy quartz is nearly always present in the Potosi Dolomite bedrock and its residuum. It occurs as 0.5 millimeter (mm) to 5 centimeter (cm) quartz crystals on numerous thin layers of chalcedony (Wagner, 1973). Barite miners referred to drusy quartz as “moory” (Tarr, 1918) or “mineral blossom” (Thompson, 1995). It is widespread throughout Missouri in the Potosi Dolomite, and is interpreted by Wagner (1973) and Kaiser and others (1987) to have been deposited following karstification that accompanied the development of unconformities, probably in Ordovician time, and is unrelated to barite-lead mineralization. Replacement of dolomite by chert is another form of silicification that occurred (Wagner, 1973).

Barite, known as “tiff” to the miners, varies in size from minute grains to large masses (up several hundred pounds), but is more commonly in pieces from about 1 to about 10 inches in size, with much of the finer material lost during processing (Dake, 1930; Weigel, 1929). Barite occurs in a variety of forms for which a variety of local descriptive terms were used (Muilenburg, 1957). Ball tiff is a botryoidal form of barite with a radiating, bladed structure (Muilenburg, 1957). Chalk tiff is a finely crystalline aggregate of barite (Ball, 1916). Other terms used are dry bone, sheep nose tiff, split tiff, and spar; names to describe the mode of occurrence are rock tiff, gravel tiff, and clay tiff (Muilenburg, 1957). Wagner (1973) describes two major types of barite: white barite, and clear barite. The white barite was deposited during the main stage of ore mineralization, and forms fine to coarsely crystalline aggregates of blade-like crystals. The white color is the result of an abundance of fluid inclusions in the crystals. Clear barite is clear because of a lack of fluid inclusions. Kaiser and others (1987) state that clear barite was also known as “glass tiff”, but “spar” is the term Washington County miners used for clear barite, according to Muilenburg (1957); “glass tiff” was used by Central Missouri Barite District miners to describe clear barite and was used by Washington County miners to describe calcite. The clear barite was both a late-stage hypogene mineral and a supergene mineral (Wagner, 1973; Kaiser and others, 1987).

Galena occurs as cubes or aggregates of cubes, known as “block mineral” (Buckley, 1908) or “cog lead” (Dake, 1930); a lesser amount of octahedral galena is present. Ball (1916) states that galena usually occurs as small cubes disseminated in chalk tiff, and less so in ball tiff. However, galena was sometimes found in masses as large as several hundred pounds (Winslow, 1894). Wagner (1973) states that galena is present in some areas, that sphalerite without galena is rare, and he describes sphalerite as layers and isolated clusters of black, greenish-black, light red, and tan crystals. Dake (1930) states that sphalerite is present in some veins but is commonly absent. Dake (1930) states that there was not much production from sphalerite, as it was difficult to separate from barite.

Oxidation of sulfide minerals to secondary minerals occurred and is mentioned in numerous places in the literature. Wagner (1973) states that nearly all the sulfides in the residual deposits were “weathered” to some degree, and that “fresh" sulfides can be found 10-15 ft into the underlying bedrock. Kaiser and others (1987) states that that the district contains “minor” sulfides that are “largely” oxidized. Tarr (1918) states that galena “always shows evidence of attack by ground water,” that galena in residuum rarely shows crystal faces, and in half of the specimens observed there was a layer of gray or white cerussite. Ball (1916) states that galena cubes commonly have rounded corners and corroded surfaces (evidence of leaching), and galena cubes are commonly partly altered to cerussite, which can be white and crystallized or a gray powder. He further states that cerussite was for many years not recognized as an ore mineral, and was thrown out on the mine dump. Dake (1930), however, describes cerussite as occurring “sparingly”, and states that anglesite has been “reported”. Wagner (1973) states that anglesite is widespread as thin, gray, earthy coatings on galena. Sphalerite is oxidized to smithsonite, which forms crusts on sphalerite, barite, and dolomite (Tarr, 1918). Dake (1930) states that most of the zinc production was from smithsonite. Zinc-ore minerals at the Valles Mines are mostly smithsonite (Kiilsgaard and others, 1967). Limonite is abundant as an alteration product of marcasite and pyrite, commonly coats barite and other minerals (Weigel, 1929), and may be pseudomorphous after marcasite or pyrite (Dake, 1930; Wagner, 1973).

Mineral Zoning, and Structural and Stratigraphic Controls of Mineralization

Wagner (1973) recognized barite textural zoning and mineralogic zoning in large, linear ore runs from 1 to at least 6 mi long and from 200 yards to 3 mi wide in the Southeast Missouri Barite District. Barite textural zoning consists of a central zone of coarsely-crystalline barite that grades (or sometimes more abruptly changes) outward to a zone of finely-crystalline barite. Mineralogic zoning coincides spatially with the barite-textural zoning, with sulfides concentrated mostly in the center of runs. Sphalerite occurs in the central parts of runs; galena is more widespread but is more concentrated in the central parts of runs and occurs in minor amounts in the outer parts of the runs. Zoning is centered on a controlling structure (a fault or concentration of joints) and complex zoning patterns may result from mineralization along intersecting structures. Wagner (1973) also recognized that individual ore deposits are not geologically isolated but are parts of ore runs. Residual ore deposits that were once part of a continuous ore run are isolated from each other by topographic lows where the ore deposit was removed by erosion. Also, an ore run may be longer than its surficial expression in the case where it extends in the subsurface, where it remains unweathered with no surficial expression.

Wagner (1973) interprets the distribution of barite textural zones and mineralogic zones around faults and zones of joints as indicating structural and stratigraphic controls of mineralization, the combination of which created a plumbing system for the ore fluids. Ore fluids would have moved up from depth along faults and joints until intersecting permeable rock through which the fluids migrated laterally, away from the structures. The zoning is a result of geochemical conditions that changed with increasing distance from the controlling structures. The stratigraphic controls of ore mineralization were the “unconformity-related” open spaces in the dolomite that developed during an earlier dissolution (karstification) event (Kaiser and others, 1987; Wagner, 1986). These open spaces are solution vugs along stromatolite structures or laterally-connected networks of fractures and solution cavities along bedding planes (Kaiser and others, 1987), where in many cases silica minerals had already been deposited.

Mining History

The mining history of the Southeast Missouri Barite District and the Valles Mines is presented in two sections-- lead mining, then barite mining, which follows the chronological order of mining. Lead-ore minerals and barite commonly occur together, and some areas that were first mined for lead were later mined for barite, with lead sometimes recovered as a by-product during barite mining. Zinc was also recovered at some lead mines, but was mostly secondary in importance to lead, if it was recovered at all, and discussion of zinc mining, processing, and production is covered in the section on lead mining rather than in a separate section on zinc. Zinc was the most important resource recovered at the Valles Mines. Copper was recovered in a few mines. Each section has three subsections: 1) the development of mining; 2) mining and processing methods, and 3) mine production and losses. The subject of most of this section is the Southeast Missouri Barite District, with specific mention of the Valles Mines where appropriate. In addition, brief mention is made of mining at the Irondale, Indian Creek, and Viburnum Trend Subdistricts of the Southeast Missouri Lead District.

Lead Mining

Early lead mining in Missouri was by shallow diggings in surficial deposits wherever they were found, mostly in the Southeast Missouri Barite District but also in other parts of southeastern Missouri, including but not limited to the Southeast Missouri Lead District, and later in central and southwestern Missouri. Because the development of mining in the Southeast Missouri Barite District is part of the broader development of mining in Missouri, some mention is made in this report of mining in these other areas, particularly at Mine La Motte (fig. 1) of the Southeast Missouri Lead District, where some of the earliest mining occurred. The distinction between the two districts is relevant for this report but was not during the time of early lead mining, as definitions of mining districts and subdistricts did not evolve until much later.

The names of the early lead mines may be singular, such as “Mine Renault” or plural, such as “Old Mines”, but in both cases generally refer to groups of diggings (shafts) and not a single shaft, as is commonly the case with modern mines. Most of the lead and zinc mines mentioned or described in this section are shown in figure 7, and in most cases these are really centers of mine activity, from several acres to several thousand acres in size (Dake, 1930), and not individual mines. These mines are listed in table 1, which also shows the primary sources of information for these mines. There were many more mines in the district than can be shown in figure 7. Most of the literature references for this section state that there were more mines than can be listed, and not all lead mines that are mentioned in the literature are described in this section; instead this section describes only those that appear to be the principal mines by virtue of production or longevity, or by being described in referenced literature rather than just mentioned. Because reliable location data for some mines are not available, either because of the age of the mines or because different sources give different locations or no locations, some mines discussed in this section are shown on figure 7 only approximately or not at all. To present a more comprehensive, yet still incomplete portrayal of the scope of lead mining in the study area, figure 7 also shows lead and zinc mines that are in the MGS IMOP database. Still, it is not possible for an inventory of old mines to be complete, given the age of the mining and incomplete record keeping; also, there are some mines listed in literature sources that have not yet been examined for the IMOP database (Cheryl Seeger, Missouri Geological Survey, written commun., June 14, 2016). Figure 7 also reproduces Ball's (1916) sketch map of lead mines in Washington County, which he states shows many but not all the mines. His map was made many years after most of the lead mining, and it would have been difficult to accurately record all mine locations, given the time that had elapsed and the incomplete records of mining that existed. Although Ball's (1916) map was just a sketch map and some of the mines may not be located precisely, it helps to illustrate the widespread extent of lead mining.

Figure 7. Map of the study area showing locations of mines of the Southeast Missouri Barite District and Valles Mines where lead, zinc, or copper was the primary metal recovered, locations in the study area of mines of the Southeast Missouri Lead District, and locations of iron mines in the study area.

Table 1. Mine name and references for lead and zinc mines of the Southeast Missouri Barite District, Valles Mines, and the Southeast Missouri Lead District described or mentioned in this report and shown in figure 7, and mining district in which the mine is located..

Development of Lead Mining

French missionaries and explorers were the first to encounter lead mines in Missouri, which was then part of French-controlled Louisiana Territory. Father James Gravier, a missionary priest, wrote an account of his voyage in 1700 and mentioned the existence of a rich lead mine along the Meramec River (Burford, 1978). At about the same time as Gravier's voyage, Pierre Charles LeSeur led the first mineral exploration of the Mississippi Valley and also was told of lead mines along the Meramec River being worked by Native Americans. Although lead deposits occur along the Meramec River and its tributaries in Franklin, Crawford, and Washington Counties, these reports may have been referring to the Big River (Park, 2006) which is a major tributary of the Meramec River and drains parts of the Southeast Missouri Barite District, the Valles Mines, and the Southeast Missouri Lead District (fig. 1).

In 1712 King Louis XIV granted a royal charter to Anthony Crozat, giving him exclusive rights to commerce, including minerals, and he appointed Sieur Antoine de La Motte Cadillac Governor of the Territory (Park, 2006). Claude DuTisne followed an old Native American trail through Washington County in 1714 and returned with samples of lead ore, but no immediate mine development followed. In 1715, La Motte led an expedition into Madison County that resulted in the discovery of lead ore at what would become Mine La Motte (fig. 1), one of the major subdistricts of the Southeast Missouri Lead District where lead ore was mined from the lower Bonneterre Formation and in places the upper Lamotte Sandstone (fig. 3) until 1959. However, Crozat went bankrupt and relinquished his charter, La Motte returned to France, and the lead ores at Mine La Motte were not developed until several years later (Park, 2006).

Following Crozat's bankruptcy, the Company of the West was formed in 1717 to promote the development of the Louisiana Territory, and claims were made of the mineral wealth in the Territory to encourage emigration from France. Lead was mined by Sieur de Renaudiere in 1719 at Cabanage de Renaudiere, which may mark the beginning of mining at what is known today as Old Mines (Showalter, 1963; figs. 2 and 7), the first settlement in Washington County (Burford, 1978). This prompted further immigration to the Territory, including a prospecting expedition in 1719-20 by the Company of St. Philippe, a subsidiary of the Royal Company of the Indies, which was formed by the merger of the Company of the West with the Company of the Indies (Park, 2006). This expedition was led by Philippe

Francois Renault, who left France with workmen and reportedly purchased slaves in Santo Domingo (Showalter, 1963), although this has been disputed by Ekberg and others (1981). Prospecting parties, led by Renault and La Motte, who had earlier prospected the Territory, were sent out from the French settlement of Kaskaskia (in what is now Illinois) on the Mississippi River. The result was the discovery of lead and the development of lead mines in the Southeast Missouri Barite District at Mine Renault (also called Forche a Renault Mine, located somewhere near the headwaters of Mineral Fork, perhaps along Fourche a Renault Creek [Ekberg and others, 1981; Park, 2006; fig. 7]), at Old Mines (together, these two are sometimes called the “Meramec Mines”, or the “Mineral Fork Mines” [Park, 2006]; their exact locations are not well established [Elberg and others, 1981]), at other places along the Big River, Mineral Fork, and Forche a Renault Creek (Showalter, 1963), and in the Southeast Missouri Lead District at Mine a Gerbora (Winslow, 1894; Burford, 1978; not shown on figure 7) and at the previously-discovered Mine La Motte (fig. 1). With these mines, which were not mines by modern standards but instead were shallow diggings in the surficial residuum, began the first period of consistent lead mining in Missouri (Burford, 1978). Referring to Old Mines, Dake (1930) stated “The area embraced in this group … covers several square miles, and the number of individual shafts and pits was very great”. By 1725 about 1,500 pounds (lb) per day of lead were smelted into pigs and carried by pack horses from mines in Washington County to Ste. Genevieve on the Mississippi River for shipment to France (Showalter, 1963). Permanent settlements were not established at these mines at this time, but a settlement was established at Ste. Genevieve (Burford, 1978). Although the Royal Company of the Indies was broke by 1731 and lost its charter, Renault continued to mine until 1744 when, because of lack of funds and attacks from Native Americans, he returned to France with most of his workers.

Lead mining continued after the closure of Renault’s mines, but was sporadic until about the end of the 18th century (Winslow, 1984). Some workers remained after Renault’s departure, particularly at

Old Mines and Ste. Genevieve, and probably operated farms during the growing season and worked the mines at other times at both the already-developed mining areas of Old Mines, Mine La Motte and Mine a Gerbora (Winslow, 1894) and at Bonne Terre (fig. 2) and Mine a Joe (Park, 2006; Mine a Gerbora, Bonneterre, and Mine a Joe are located in what would become the Old Lead Belt and are not shown in figure 7). Park (2006) states that 100,000 lbs of lead were produced from the Meramec Mines in 1752. In 1762 France ceded her land holdings on the east side of the Mississippi, but not including New Orleans, Louisiana, to England and ceded her land holdings on the west side of the Mississippi to Spain. Many French settlers east of the Mississippi migrated west to what is now Missouri, preferring Spanish rule to British rule. Mining by the French continued under Spanish rule, including renewed mining at Mine La Motte by Francois Valle in about 1763 (Park, 2006). Valle had migrated from Quebec to Kaskaskia and later built a cabin at what is now Valles Mines (fig. 2 and 7) in 1749 to buy lead from Native Americans who mined it in the area. The Valles Mines would later become an important zinc and lead mining area.

As early as 1760 but perhaps between 1775 and 1780 (Park, 2006), Francis Azor, called “The Breton” because of his birthplace in Brittany, France, and Peter Boyer discovered lead at the surface at what would become known as Mine a Breton (sometimes written as Mine a Burton), the name later changed to Potosi (Showalter, 1963; Carrollscorner.net, n.d.; Heathstone Legacy Publications, 2004; Park, 2006; figs. 2 and. 7). Other settlers came and a mining camp developed along the south side of what would be named Mine a Breton Creek, which flows through Potosi, and on the hill known as The Citadel. Mine a Breton became a larger center of mining activity than Mine La Motte, covered an area of several thousand acres with many shafts (Dake, 1930), and a road was built from Mine a Breton to Ste. Genevieve in 1791 (Park, 2006) to transport lead for shipment to New Orleans. Ore was discovered at Mine a Robina at about the same time as the discovery at Mine a Breton (Winslow, 1894; fig. 7).

Winslow (1894) states that Mines a Layne and Mine a Maneto in St. Francois County and Mine a La Platte in southeastern Washington County, all of which are probably in the Southeast Missouri Lead District and not shown in figure 7, were started in the last few years of the 19th century.

A major advancement in lead mining in Missouri was the arrival of Moses Austin, an American, who transformed lead mining from a seasonal endeavor carried out between the end of the harvest and winter to a year-around industry (Burford, 1978; Gracy II, 1992). Austin was originally from Connecticut and had been operating lead mines in Virginia, when he heard of the rich lead deposits in Missouri. He visited Missouri in 1797, obtained a land grant from the Spanish government of over 6,000 acres northwest of Potosi, including a large part of Azor's previous grant at Mine a Breton, moved his family to Mine a Breton in 1798 to become the first permanent white settlers in Potosi (still called Mine a Breton at that time), and built a large home there in 1799 (Showalter, 1963; Heathstone Legacy Publications, 2004). In describing Mine a Breton, Austin stated "The mines may be said to extend over two thousand acres of land; but the principal workings are within the limits of one hundred and sixty acres; and perhaps no part of the world furnishes lead ore in greater quantities and purity" (Stoddard, 1804). Until this time most of the ore in the district was dug from shallow diggings, usually only 10 ft deep or less (Winslow, 1894). Austin sank the first shaft in Missouri to a depth of 80 ft in 1799, and erected a shot tower about one mi northwest of Potosi (Hearthstone Legacy Publications, 2004; a shot tower is tall structure from which molten lead was dropped into a pool of water, forming spheres of lead that were used as shot in firearms). Austin also established the port town of Herculaneum on the Mississippi River in 1809 (fig. 2) and built a shot tower there. Most of the lead produced in Potosi and surrounding areas was shipped over a newly-built road to Herculaneum for shipment down the Mississippi River (Park, 2006).

Spain transferred ownership of the Louisiana Territory back to France in 1801, who shortly thereafter sold the Territory to the United States in 1803 as the Louisiana Purchase. This prompted Austin's 1804 report to Congress on the condition of mining in the area (Stoddard, 1804) in which four mines of the Southeast Missouri Barite District (Mine a Breton, Mine a Robina [Stoddard, 1804 called this Robuna], Old Mines, and Mine Renault) and 6 mines of the Southeast Missouri Lead District are described. A leasing system was instituted by the U.S. government in 1807 by which land was leased for up to 3 years with a 10% royalty paid to the government. This system was not welcomed by those with previously-valid mining claims, and others ignored both property rights and government regulations, with the result that mine productivity lagged for several years (Park, 2006; Burford, 1978). Still, other mining areas in the Southeast Missouri Barite District were developed in the early part of the 19th century, including Fourche a Courtois in southwestern Washington County (also known as the Palmer Mines or the Shirley-Palmer), the French Diggings and La Beaume Mines at what would become known as the Richwoods Mines in northeastern Washington County, the Shibboleth Mines, Mine a Straddle, Bellefontaine Mines, Elliot's Mines, Cannon's Mines, and Mine a Martin in Washington County, Gray's Mine in Jefferson County, and others (Burford, 1978; Showater, 1963; Winslow, 1894; fig. 7).

In describing the state of the lead mines of the region (all of southeastern Missouri, but particularly Washington County) in 1819, Schoolcraft (1819) states that the mines are "worked in a more improved manner than at any former period", "are more extensive than when the country came into the hands of the United States", that "every season is adding to the number of mines", that "the ores may be considered of the richest kind", that "we cannot resist the belief that in riches and extent, the mines of Missouri are paralleled by no other mineral district of the world", and describes the region as "the land of ores—the country of minerals". He lists 39 lead mines and 34 lead furnaces in Washington

County as of 1819, of which the most “noted and extensive” mines are: Mine a Burton (Breton; apparently this includes Moses Austin’s mines), Shibboleth Mines, LaBeaume’s Mines (Richwoods Mines), Old Mines, Mine a Robina, Mine a Straddle, Mine Renault, New Diggings, Mine a Liberty, Cannon’s Mines, Mine Silvers, and Mine a Martin (fig. 7). Schoolcraft (1819) included the Palmer (Forche a Cortois) mines (fig. 7) in his list of 39 mines in Washington County, but did not include them in his list of the most “noted and extensive” mines in Washington County. There had been a rush to the Palmer area in 1814 and dozens of small lead mines were opened over a large area. Schoolcraft (1819) noted the occurrence of zinc ore and “tiff” (barite) in some of these 39 mines.

Winslow (1894) states that lead production in the years from 1820 to 1830 was probably about the same as in the preceding years, with some increase in the latter part of the decade because of an increase in the import duty for lead. Deposits were discovered and mining initiated at Sandy Mines in Jefferson County and at mines of the Valles Mines (Bisch’s Mine, Perry’s Mine, and the Valles Mines [proper]) in northern St. Francois County (fig. 7; Winslow, 1894)). The literature on the Valles Mines is unclear – the mining area is named after Francois Valle who came to the area in 1749 to buy lead from Native Americans, but it is unclear if any mines were operated at that time. Instead, Valle operated the Mine La Motte mines about 30 miles to the south (fig. 1). Although Litton (1855) and Winslow (1894) state that the first mining at Valles Mines (probably meaning the Valles Mines [proper]) began in 1824, the Valles Mining Company records state that there was earlier mining followed by the sinking of a shaft in about 1819, that a “major discovery” of lead there and at the Mammoth Mine (fig. 7) several miles to the northwest led to the sinking of other shafts, and that “Valles Mines became one of the most significant areas of lead production in the state, as well as one of the most long-lived” (State Historical Society of Missouri, 2013). Zinc became a valuable resource after the Civil War, and the Valles Mines became an important supplier of zinc as well as lead, with at least some production up until the 1920’s.

Other mines that began production in the 1820s' are the McCormick Mines (McCormick's Diggings) and Nashville Mines in Jefferson County (Winslow, 1894; fig. 7). The Palmer Mines had grown into an important mining area and 1831 Palmer was a community of 200 miners (Winslow, 1894). Mining continued there into the early 1900's, including the mining of zinc ore in the latter years after the value of zinc had been realized.

The period from 1830 to 1850 was a period of increased lead production in the Southeast Missouri Barite District and elsewhere in southeastern Missouri, and saw the discovery of lead and initiation of lead mining in southwestern Missouri in 1848 (Winslow, 1894; Park, 2006). Winslow (1894) states that new mines in Jefferson County include Howe's Diggings, Frissel Mines, Tarpley Mines (of the Valles Mines), Lee's Diggings, and Mammoth Mines (the Valles Mining Company records places the initiation of mining at the Mammoth Mines several years earlier [State Historical Society of Missouri, 2013]; fig. 7). Winslow (1894) also mentions several other mines that were being worked during that period: Perry's Mine and Bisch's Mine, both of the Valles Mines, in St. Francois County, and Old Mines, Shibboleth Mines, the Casey and Clancey's Diggings, Shore's Diggings, LaBeaume's Mine, French Diggings, and the Fourche a Courtois Mines (Palmer Mines) in Washington County (fig. 7).

The period of 1850 to 1860 saw the beginning of lead mining in southwestern Missouri (Tri-State District) and continued mining in the southeastern part of the state (Winslow, 1894). The status of lead mining in Washington, Jefferson, and St. Francois Counties in the mid 1800's is provided by Litton (1855), who visited and described many, but not all of the mines in the district, and by Swallow (1859) who compiled data from Litton (1855) and others. Litton (1855) and Swallow (1859) describe the depths of shafts at some mines, apparently using the term "shaft" to include a range of depths, from shallow pits (diggings) a few ft deep to shafts in rock over 100 ft deep.

Litton (1855) describes the lead mining in Washington County to have been almost uninterrupted since it began, and to have occurred throughout most of the county. He states that it would not be possible to describe all the mining that had occurred up to that time, that Washington County “may be considered as one extensive lead diggings”, and that “there is scarcely a township on which there has not been, at some period, more or less mining and, perhaps, scarcely a section on which mineral has not been actually found”. He provides brief descriptions of a number of mines that he visited or for which he could obtain reliable information, and stated that it is “but a small list of the localities, at which, during some period or other, mining has been carried on”. Litton (1855) also gives some production figures. Most of the mines which he describes are located on figure 7. The Old Mines concession (Old Mines) was one of the first mining areas in Missouri, dating back to the early 1700’s. Mining was still occurring in 1854, with about 20 shafts as deep as 60 ft. The Shibboleth Mines, which had first been worked in the early 1800’s, were still being worked in 1854 with shafts as deep as 50 ft over an area about ¾ mi long northwest to southeast and about ¼ mi wide. The Bellefontaine Mines, which also began in the early 1800’s, were in an area of about 40 acres with shafts as deep as 75 ft, although most of the mining may have been in the residuum. The Cannon Mines, which also date back to the early 1800’s, extended for about 1½ mi north-south by about 3/4 mi east-west, with most of the ore coming from the residuum at depths up to 15 ft. The Scott and Bee Diggings covered about 160 acres, with shafts as deep as 65 ft. Litton (1855) states that there was little mining being done at that time in the immediate vicinity of Potosi, but the Potosi Lead Company began a mining operation for a short time in 1853, consisting of an open cut and several shafts. Previous mining at Burt’s diggings west of Potosi (not on fig. 7) left an area “literally covered with holes”; a little mining was still being done in 1855 from two shafts in the rock, up to 55 ft deep. A short distance southwest of Potosi was the Pierce and Willoughby’s Diggings, on about 10 acres of Moses Austin’s original land grant. Mining had occurred over the years, and was being conducted in 1855 from a 110-ft deep shaft. Mining at New Diggings, previously described by Schoolcraft (1819) was over an area of about ¼ mi east-west by about ½ mi north-south, and was still active in 1854. Lupton Diggings extended about a ½ mi north-south by about 150 yards wide, with the deepest shaft 79 ft deep (fig. 7). Adjacent to this was mining in the "Sixteenth Section", which consisted of 7 shafts an average of about 64-ft deep, and with drifting up to 300 ft, described by Litton (1855) as "more extensive than at most points in Washington County". Casey and Clancey's Diggings, which extended over an area about ½ mile east-west by a ¼ mi north-south, previously had two shafts 90-ft deep, but mining was being conducted at shallower depths in 1855. To the east was Cook's Diggings, with shafts just 20 ft deep. The Brock Digging's which covered about 10 acres and which had not been worked since 1841, were in the residuum only. Shore's Diggings consisted of several shafts as deep as 100 ft, with drifts up to 160-ft long. The Prairie Diggings consisted of five or six shafts from 28 to 40 ft deep. Shafts of the Elliot's Mines were up to 60 ft deep, and at least some of the mining was in rock. Litton (1855) mentions, but does not describe, that there were several mines along both sides of Forche a Renault Creek and that two sections were "covered" with shafts, but more precise locations are lacking.

Litton (1855) lists 23 mines of the Fourche a Courtois (Palmer) Mines over a large area in the southwestern part of Washington County (fig. 7), and provides descriptions of several of these: the Ismael Diggings (the most productive in "recent" years), the Pigeon Roost Diggings and Trash Diggings (also very productive), the Strawberry Diggings (on the same ridge as the Pigeon Roost and Trash Diggings), the Flint Hill Diggings and Bit Diggings (on the same ridge as each other), Bluff Diggings, Polecat Diggings, Coffee-Pot Diggings, Maury Diggings, and Grave-Yard Diggings (fig.7) . This had been an important mining area for a number of years, mentioned first by Schoolcraft (1819), and continued to be important for many more years. The MGS IMOP database lists about 180 lead, zinc, or lead and zinc past producers in the Palmer area (fig 7), exceeding the 23 mines listed by Litton (1855). Dake (1930) contains a map showing the location of 94 lead diggings (these locations also are in the MGS IMOP database) and several barite mines in the Palmer area. Although there were as many as 200 miners in the Palmer area in 1831, there were only about 30 miners employed in 1855 (Litton, 1855). Mining was in the residuum and rock, and shafts were as deep as 146 ft (Winslow, 1894).

Litton (1855) states that lead mining had been active at the Richwoods Mines for the previous 40 years, and that “the points at which mining has been carried on are very many”. Included in this is the La Beaume Mines (fig. 7), active since the early 1800’s and covering an area of about 30 acres; mining was as deep as 80 ft, although most of the mining was from 6 to 20 ft deep. Also included in the Richwoods Mines is the French Diggings (fig. 7), also dating back to the early 1800’s. Litton (1855) states that these mines had not been worked in recent years, but had “yielded abundantly” from shallow diggings prior to 1843. Other diggings in the area are briefly mentioned. The mines described by Litton (1855) are listed, without description, by Swallow (1859).

Three mines are described by Litton (1855) as being the principal mines in Jefferson County: Sandy Mines, Mammoth Mine, and Tarpley Mines (of the Valles Mines) (fig. 7). Mining at the Sandy Mines was along a line nearly 1 mile (mi) in length, first as diggings in the clay residuum and later in the rock. A cross section of the Sandy Mines in Litton (1855) shows several shafts, and the depth of mining was as great as 115 ft. The MGS IMOP database indicates that there were more than 100 shafts by 1863. This mine is an outlier with respect to most of the mines of the Southeast Missouri Barite District; it is in the Jefferson City or Cotter Dolomites, or both (fig. 3) rather than the Potosi or Eminence Dolomites which host most of the ore, and plots outside the district boundary shown in figure 2. Litton (1855) shows a cross section of the Mammoth Mine with a single shaft that is over 60 ft deep, and the length of the mining is given as more than 530 ft. Mining had been inactive there since 1852.

The Mammoth Mine plots in the outcrop area of the Gasconade Dolomite, and is therefore also in rocks younger than most Southeast Missouri Barite District ore deposits. The Tarpley Mines had several shafts, the deepest of which was 180 ft. Lead mining was more widespread in Jefferson County than is indicated by the three principal mines described by Litton (1855). The MGS IMOP database has many more lead mines, and Swallow (1859) lists 42 mostly previously-worked mines in Jefferson County, including the three described by Litton (1855), and provides brief descriptions of 19 of these: the Gopher Mines, Mammoth Mine, Sandy Mines, Howe's Diggings, Yankee Diggings, McCormick's Diggings (different than nearby McCormack Diggings in St. Francois County), Lee's Diggings, Robinson's Diggings, Kelly's Diggings, Frissel's Mines, Nashville Mines, Gray's Mines, and the following mines of the Valles Mines: Poston and Tyler's Mines, Tarpley Mines, Garrity and Butcher's Diggings, Bisch and Daly Mines (different than the nearby Bisch's mines in St. Francois County), Bogy's Diggings, Rocky Diggings, and Miller's Diggings (fig.7). In addition to these mines, Parizek (1949) included the Garatee Mines and the Corn Stalk Diggings in Jefferson County as part of the Valles Mines (fig. 7). Winslow (1894) also describes the Garatee Mines.

The principal mines in St. Francois County described by Litton (1855) are mines of the Valles Mines: the Valles Mines (proper), Perry's Mine, Bisch's Mines, and the McCormack Diggings (fig. 7). The Valles Mines (proper), Perry's Mine and Bisch's Mines were on contiguous properties in northern St. Francois County, apparently mining the same deposit on about 50 acres. There were at least 30 shafts at these three mines by 1855, the deepest of which was 170 ft. Litton (1855) described the Valles Mine (proper) and Perry's Mine as "more generally known than any other lead mines in Missouri; known, not only on account of the length of time during which mining has been carried on, but also by the large amount of ore which has been obtained". The McCormack Diggings (different than McCormick's

Diggings in Jefferson County) consisted of 65-ft and 85-ft deep shafts in 1855. Swallow (1859) does not describe mines in St. Francois County.

Referring to Missouri in general and not necessarily only the Southeast Missouri Barite District, Litton (1855) states that zinc is found with lead, particularly at Perry's Mine, and mentions a few other places where zinc was known at that time to exist, and that at many places zinc is the most abundant ore metal. The potential for zinc had not yet been fully realized, as he speculates that the recently-discovered application of zinc oxide as a paint pigment, and other recently-discovered uses of zinc may create a greater demand for the metal.

The lead mines in southeastern Missouri continued to operate during the Civil War, though at a diminished rate of production. Winslow (1894) does not provide much detail, but specifically mentions the Valles Mines (proper) in St. Francois County and the Darby Mines in Jefferson County as continuing to operate during this period, along with some other mines. The state of lead mining in the Southeast Missouri Barite District for the next approximately 30 or 40 years is somewhat ambiguous: Showater (1963) states that surface lead deposits in Washington County "ran out" at the close of the Civil War and lead mining and smelting declined as the barite industry began to develop, and Buckley (1908) states the production in Washington County decreased during the period from 1869 to 1906. Winslow (1894), however, referring to the "Washington-Jefferson County Sub-District" in which he includes northern St. Francois County and Crawford County, stated that the rate of production had been "uniformly large for the past hundred years, and is maintained up to the present time". Although production may not have diminished during these years, the importance of the Southeast Missouri Barite District did diminish because of increased production from other districts in Missouri. The organization of the St. Joseph Lead Company in 1864 and the introduction of the diamond drill in 1869 led to the discovery of subsurface lead and zinc deposits of the Southeast Missouri Lead District and the large-scale mining of these deposits. Also, large-scale mining in the Tri-State District in southwestern Missouri, northeastern Oklahoma, and southeastern Kansas began in the 1870's (small scale mining had been active for about 20 years), as the value and uses of zinc increased (this was a zinc-dominant district rather than a lead-dominant district). Winslow (1894) does not provide much information about what mines of the Southeast Missouri Barite District and the Valles Mines were operating during the last 20 or 30 years of the 19th century, but does mention a few: Perry's Mine and the Valles Mines (proper) in St. Francois County (which produced much zinc), the Frumet Mines in Jefferson County (fig. 7), and the McArthur Mines (not shows on fig. 7), which Winslow (1894) describes as an area of 10,000 acres that includes Mine a Breton and other mines in the Potosi area. The Tenth Census in 1880 (Winslow, 1894) shows 14 mines in Washington County, 4 in Jefferson County, and 3 in St. Francois County (this includes the St. Joseph Lead Company Bonne Terre Mine of the Old Lead Belt of the Southeast Missouri Lead District). Dake (1930) stated that the maximum annual production of the Palmer Mines was in 1873.

Lead mining in the Southeast Missouri Barite District declined in the early part of the 20th century as mining in the Old Lead Belt, Mine La Motte, and the Tri-State District expanded. Dake (1930) states that the last important operations at Old Mines were about 1901-02, and that shallow lead was picked up occasionally. Killsgaard and others (1967) state that a few carloads of zinc-carbonate ore were shipped from the Palmer area in 1915 and 1916, but that no lead mines in the Potosi-Palmer area had been productive in recent decades. Dake (1930) states that there was no systematic lead production from the Palmer Mines during his field work (1922-28); The Valles Mines operated into the early part of the century – Killsgaard and others (1967) state that the Valles Mines were most active in the late 1800's and 1909-17, and except for some mine dump material that was shipped during World War II, the area had been inactive since 1917. Park (2006), however, states that intermittent zinc mining took place until 1948. Some mine activity took place at the Krueger Mine (fig. 7) in 1917, where lead had been previously mined at shallow depths (Ballinger, 1948). A shaft was sunk to 112 ft, some drifting was performed at this depth, and about 100 tons of lead ore was shipped. Exploration drilling for zinc was conducted at that time, then later in 1930, and still later in 1947, but no additional mining was conducted. Dake (1930) describes several mines that were no longer active: two Smith Diggings (two mines with the same name), Heffner Diggings, Grainger Diggings, Gulf Prospect, Masson Diggings, Benning’s Diggings, Nigger Wool Diggings, Forker Diggings, Furnace Creek Diggings, and Plaffy Diggings (fig 7). Lead was recovered from some barite diggings, and apparently the practice of digging for lead also continued, at least to some extent—in describing the lead mines of Washington County, Ball (1916) stated that “mining methods of a century ago prevail”, and that while many miners left Washington County to work in the large underground mines in St. Francois County (Southeast Missouri Lead District), others did not, preferring to work for themselves in the diggings.

In an attempt to supply lead and zinc during World War II, mine waste from old mines were transported to what was called “The Chat Pile” at Valles Mines for processing (Valles Mines, Missouri USA, 2015). This washer operation was not very successful, and fine-grained lead, zinc (in the form of smithsonite), and barite were washed with the clay waste into to a stream downstream from the plant. Later, a study was done to evaluate the potential of processing old mine dumps in the Valle Mines area for lead, zinc, and barite recovery (Weigel, 1977). The estimated ore grades were 1-2% galena, trace to 0.5% anglesite, trace to 0.5% cerussite, 5-8% smithsonite, trace to 1% sphalerite, and 10-15% barite.

The Irondale Subdistrict of the Southeast Missouri Lead District is in southeastern Washington County, where the bedrock formations are the Cambrian Bonneterre Formation and Lamotte Sandstone. There is little information in the literature concerning the Irondale subdistrict; the MGS IMOP database shows 2 underground lead mines – the Irondale Mine and the Eversole Mine. Ore deposits were small concentrations around igneous knobs (Snyder and Gerdemann, 1969), and the period of underground mining in the subdistrict may have been brief. Buckley (1908) shows production by the Irondale Lead Company only in 1902. Surface mining probably preceded underground mining in the Irondale Subdistrict, which was the case in the Old Lead Belt and Mine La Motte Subdistricts of the Southeast Missouri Lead District where, beginning in 1869, diamond core drilling showed that the surficial deposits continued to greater depths.

Exploration by the St. Joseph Lead Company to replace depleting lead ore reserves in the Old Lead Belt resulted in the discovery in Washington County of the Indian Creek Subdistrict of the Southeast Missouri Lead District in 1948 (figs. 1 and 2). The Indian Creek Subdistrict consists of two underground mines where ore in the lower Bonneterre Formation and upper Lamotte Sandstone was mined–the Indian Creek Mine and the nearby Goose Creek Mine. The mines, which were accessed from a 950-ft deep shaft, were operated from 1953 to 1982 (Hagni, 1995; Kiilsgaard and others, 1967) and were collectively called the Indian Creek Mine.

Continued exploration resulted in the discovery of the Viburnum Trend Subdistrict of the Southeast Missouri Lead District. Several mines were developed, including the Viburnum No. 29 Mine, which is the northernmost mine of the Trend and is in southwestern Washington County. Mine production began in 1964 from a 595-ft deep shaft (Killsgaard and others, 1967).

Lead Mining, Processing, and Smelting Methods

In the earliest days of mining, lead ore probably was simply removed from the surface of the soil. In his 1804 report to the U.S. Congress describing lead mines in “Upper Louisiana”, Moses Austin states that ore occurs within two ft of the surface at Mine a Breton, and “In short, the country for twelve of fifteen miles round the mine a Burton exhibits strong appearances of mineral. In all the small creeks mineral is found washed down from the hills, and it is not uncommon to find in the draughts leading to creeks and rivers, and in the gulleys made by the spring rains, mineral in pieces from ten to fifty pounds weight brought down by the torrents. Some hundreds have been collected in this way" (Stoddard, 1804). Ball (1916) described these ore occurrences as "galena pebbles", which, along with "blossom rock" (drusy quartz) were used as prospecting guides by tracing their occurrences upstream to their source.

Lead mining in the Southeast Missouri Barite District and the Valles Mines was primitive by modern standards, and production at individual mines was small compared to the underground mines of the Old Lead Belt and Viburnum Trend. Still, lead mining was widespread and long in duration, from the early 18th century into the early 20th century (Ball, 1916). Mining was commonly seasonal, taking place when men were not engaged in farm activities. Others, particularly the later, larger and deeper mines employed a larger number of men and probably operated continuously. Slaves were used in some mines before the Civil War.

The earliest lead mines were "diggings" (also called "pits" or "shafts") in the residual soil and were normally 15-20 ft deep (Schoolcraft, 1819). Round holes about 4 ft in diameter were dug with pick and shovel, and a hand windlass and bucket were used to hoist material to the surface. Two men normally worked a "digging", one in the shaft and the other at the surface hoisting the ore and cleaning it to separate it from other minerals and clay. Some of the deeper shafts employed a horse whim or a steam-powered windlass to hoist the ore to the surface (Ball, 1916). The shafts were normally, but not always, dug to bedrock where the ore was commonly concentrated, and drifts about 4 ft by 4 ft were dug a short distance away from the bottom of the shafts, undermining the residuum. When it became too dangerous to drift any further, the shaft was abandoned and the process was repeated a short distance away, until a large area was covered with pits (Ball, 1916). Not all shafts were productive; sometimes prospective shafts were dug following a fissure or some other surficial feature that might indicate ore at depth (Ball, 1916). Pumps were not common for many years, so work normally stopped if groundwater was encountered. Although there were sometimes indications that the ore continued deeper in the bedrock, work normally stopped at the top of bedrock and a new shaft was started. Mining by digging with pick and shovel was apparently still practiced in the early 20th century, as it is described in the present tense by Ball (1916).

The first shaft that was more like a modern shaft was dug reportedly to 80 ft at Mine a Breton by Moses Austin in 1799 (Winslow, 1894). Although Schoolcraft (1819) states that the ore was in crevices in rock, which he describes as both compact and in places friable (weathered), Thompson (1992) maintains that Austin's shaft went only to about 40 ft depth and stopped at the rock, although the mining did follow deeper ore in crevices or soft rock. Winslow (1894) mentions that "deep shafting was undertaken" in Missouri during the period from 1830 to 1850. From Litton's (1855) descriptions of some mines, with shafts as deep as 170 ft (Valles Mines) and up to several hundred feet of lateral drifting, it is apparent that some mining had progressed into the rock by that time. Litton (1855) estimated that three-fourths of the 'mineral" mined in Missouri up to that time had come from diggings in the residuum, inferring that one-fourth had come from the mining in rock. While the diggings at Potosi were "practically numberless", more mining had been done in rock during "late" years, with shafts 100 or more ft deep (Winslow, 1894). The Jumbo shaft at the Parole Mine (fig. 7) of the Palmer Mines was 146-ft deep (Winslow, 1894). The depths of many other shafts that were deep enough to have gone into bedrock and descriptions of lateral drifting are given in the literature, particularly Litton (1855) and Winslow (1894).

The material brought to the surface consisted of lead ore, which was mostly galena, but it also had lesser quantities of cerussite and anglesite mixed with clay, dolomite, and associated minerals, including druzy quartz, zinc ore and barite. Galena was cleaned by hand by "cobbing" with a hammer to remove as much clay and other non-ore material as possible to prepare the galena for smelting, and the remaining "waste" material was discarded in dumps. This included cerussite, anglesite, zinc ore and barite, until the value of these minerals was realized and they also were recovered. Winslow (1894) reports that the value of cerussite was first realized in 1838. Jigs also were used to "concentrate", or clean the ore of waste material. Winslow's (1894) first mention of jigs states that crude hand jigs were universally used by the 1860's and were still common as of 1894, but provides no further details such as when they were first used or how efficient they were. Park (2006) also describes the use of hand jigs and the "Parson's mechanical jig" which was introduced later and was used at least at Old Lead Belt mines. The IMOP database mentions 5 locations where there were "mills", two of which were called "Joplin-type mills" (fig. 8).

Figure 8. Map of the study area showing locations of lead furnaces, zinc furnaces, and lead mills of the Southeast Missouri Barite District and Valles Mines, locations in the study area of mines and tailings lakes of the Southeast Missouri Lead District and the Pea Ridge iron mine tailings lake.

Smelting of the lead ore to elemental lead was first done using a log hearth, also called a log furnace, which is described by Schoolcraft (1819) and Winslow (1894; fig. 9). The log furnace was an inclined hearth on a sloped hill with stone walls on the front and the two sides. Wooden logs were placed in the furnace, a charge of lead ore consisting of normally about 5,000 lbs of galena in pieces averaging 15 lbs in weight was placed on the logs, more logs were placed over the ore, and a fire was started. The ore was "roasted" at low temperature for several hours to remove the sulfur by oxidizing the galena to lead oxide, and then the temperature was raised for several hours to reduce the lead oxide to elemental lead in a molten state. The molten lead fell through the wood and ashes to a groove in the floor of the hearth, through which it flowed downslope to an iron mold where the lead was formed into pigs. The entire process took 24 or more hours. After smelting the ore, the furnace was cooled, the ashes removed, and the furnace was charged again. A log furnace was inexpensive to build and could be built almost anywhere, and was the only type of furnace used until 1798 (Winslow, 1894). Log furnaces do not appear to have been permanent structures like the Scotch hearths and air furnaces that would later be built, so they were probably built wherever there was mining and replaced as they wore out. For this reason and the fact that these were used during the early years of mining when records generally were not kept, the numbers and locations of these furnaces are not known and a map showing the locations of these furnaces is not given in this report. Considering that mining locations were widespread and that mining had been ongoing since about 1720, there probably were many log furnaces in the Southeast Missouri Barite District and the Valles Mines.

Figure 9. Log and ash furnaces

Log furnaces were inefficient. Winslow (1894) described them as an “improved form of campfire”, and estimated that only about 50 percent of the lead in the ore was recovered, the remainder was lost to the ashes (slags) and to volatilization. Given that galena is about 87 percent lead, that equates to about 43 pounds of lead recovered per 100 pounds of galena. Using percentage recovery in a different way, Park (2006) stated that recovery was 35 percent, meaning 35 lbs of lead recovered per 100 lbs of galena ore. Ingalls (1908) estimates that the grade of ore fed to the log furnaces was about 80 percent lead, or 1,600 lbs of lead per ton of ore, and that the yield of the log furnace was only 700 to 800 lbs of lead, (less than 50 percent), less than the 98 percent extraction rate for smelters operating in other districts in 1908.

About twenty log furnaces were in operation near Potosi when Moses Austin arrived in 1798 (Burford, 1978). Austin was attracted to the area not only because of the richness of the ore but also because of the abundance of ashes from the log furnaces that the French had been using up to that time, which contained lead and could be smelted for a profit. Austin built two, more efficient reverbatory furnaces, one for smelting primary ore, the other for smelting ashes (called an “ash furnace”; Park, 2006; fig. 9). The ashes from the log furnace, which contained lead already in an oxidized form, were crushed, washed, and placed in the ash furnace in layers alternating with crushed sand or chert (Robertson, 1894a). A wood fire was started, and after about two hours the slag was tapped and the molten lead was recovered, which was about 15 percent of the original concentration of the ore (Schoolcraft, 1819), bringing the recovery up to about 65% (65 lbs of lead per 100 lbs of galena; Park, 2006). An ash furnace thus supplemented the log furnace (Ingalls, 1908) and could be operated continuously for about fifteen to twenty days, but wore out rapidly and needed to be rebuilt. By 1802 all but one of the log furnaces at Potosi had been closed, and Austin was smelting almost all the ore produced in the area. Just how much of the ashes were processed by Austin is unknown, as one of his partners may have removed much of the ashes prior to Austin’s arrival (Park, 2006).

Log and ash furnaces, sometimes collectively termed a “log and ash furnace” were used in Missouri for many years but were gradually replaced by other furnaces. Most of the later furnaces which are described in this report are shown in figure 8, but many of these are located only approximately because of imprecise location information. The furnaces identified by number in figure 8 are listed in table 2, which shows principal references for these furnaces. Figure 8 also shows furnaces in the IMOP database; many of these correspond to furnaces described in this report and identified by number in figure 8 and listed in table 2, but some do not.

Table 2. Furnace name, resource smelted, type of furnace, and references for furnaces described in this report and shown on figure 8.

Litton (1855) states that the log and ash furnaces were replaced by the Scotch hearth or by the reverbatory furnace; Robertson (1894a) classifies the ash furnace as a type of reverbatory furnace, and Garlichs (1917) calls the ash furnace a crude type of reverbatory furnace, so Litton (1855) may be referring to the ash furnace being replaced by another type of reverbatory furnace such as an air furnace. Without stating the type of furnace, Park (2006) states that there were thirty-eight lead furnaces in Washington County in 1819. The Scotch hearth may have been in use in Washington County before 1819, but the first known Scotch hearth in Missouri was Manning's furnace at Webster (the name of this town was later changed to Palmer) which was built in 1836 (fig. 8); three log and ash furnaces operated at Webster previous to 1837 (Litton, 1855; Ingalls, 1908). Litton (1855) states that there was only one log and ash furnace in southeastern Missouri in 1855 (Higginbotham's Furnace; fig. 8), although Robertson (1894b) reports that a log and ash furnace was still in use at Cadet in Washington County in 1864 (fig. 2).

The Scotch hearth, more properly called the American-Scotch hearth (Ingalls, 1908) and sometimes called a blast furnace, used a blast of hot air, which was powered either by water, steam, or horse power (Litton, 1855). The roasting and reduction of the ore was simultaneous rather than in two steps, as with the log furnace (Robertson, 1894a). Robertson (1894a) estimates that the recovery of lead by a Scotch hearth was 80-90 percent of the lead in the ore with 10-20 percent loss to slag and volatilization, but Winslow (1894) quotes two different estimates of 67 and 70 percent recovery. Ingalls (1908) states that the Scotch hearth did not immediately replace the log and ash furnace and suggests that the reason is that they did not provide an "overwhelming advantage". Slag was at least sometimes re-smelted in a slag furnace. This type of furnace is not described; it may have been a Scotch hearth (or later, an air furnace) that was dedicated to smelting slag, and therefore called a slag furnace.

Litton (1855) lists three furnaces in Jefferson County, two furnaces in St. Francois County, and fourteen furnaces in Washington County that were operating in 1855. Most are specified as Scotch hearths, one a log and ash furnace, and a few were unspecified, but most of these likely were Scotch hearths. The furnaces in Jefferson County are: a Scotch hearth and slag furnace that smelted ore from the Valles Mines (proper?) in nearby St. Francois County (Litton [1855] does not give a precise location of the furnace; Valles Mines, Missouri, USA, 2014; Missouri Department of Health and Senior Services, 2005; Robertson, 1894b); a Scotch hearth at the Mammoth Mine; and a furnace (probably a Scotch hearth) at the Sandy Mines (fig. 8). The furnaces in St. Fancois County are the Perry's Mine Furnace (a Scotch hearth) and the Bisch's Mine Furnace (Litton [1855] states that this was a reverbatory furnace, which could mean an ash furnace or an early air furnace; Park [2006] states that this was a Scotch hearth). These two plus the Valles Mines (proper?) furnace in Jefferson County make three furnaces in the Valles Mines. The furnaces in Washington County (located approximately on figure 8) are: Higginbotham's Furnace at Fertile (Litton [1855] and Park [2006] state that this was a log and ash furnace, and Park [2006] also states that a Scotch hearth was built there in 1837); T&W Murphey's Furnace, a Scotch hearth; Long's Furnace at Old Mines, a Scotch hearth; C. White's Furnace at Old Mines, a double Scotch hearth; McIlvane's Furnace (previously known as Dunkiln's furnace), a Scotch hearth; Deane's Furnace "in the neighborhood" of Potosi, a Scotch hearth; Kennett's Furnace at Shibboleth (probably a Scotch hearth but this could be the log and ash furnace that Robertson [1894b] stated was operating at nearby Cadet in 1864; Boase's Furnace on Mill Creek (not located on figure 8 because of the unspecific location), a Scotch hearth which replaced an earlier furnace; Hopewell Furnace, also known as Evan's Furnace (Park, 2006), a Scotch hearth and slag furnace; Manning's Furnace, a Scotch hearth at Webster (Palmer) that smelted ore from Fourche a Courtois (Palmer) mines beginning in 1837; Walton's Furnace, unspecified but probably a Scotch hearth, which smelted ore and slag from the Fourche a Courtois (Palmer) mines beginning in 1841; Creswell's Furnace, a Scotch hearth; Casey and Clancey's Furnace, a Scotch hearth; and Richwood's Furnaces (Litton [1894] lists this as one furnace of an unspecified type but states that there have been two furnaces there – one operated at that time by Mr. P.E. Blow, probably a Scotch hearth, and one formerly belonging to Mr. Roussin [unclear if it was still operating in 1855]) in the Richwoods Mines area. Annual production statistics dating back a few years to as far back as 1837 are given for most of the furnaces Litton (1855) lists, and further descriptions of these furnaces indicate that smelting had been active at some of these locations for a longer period, since 1819 at one furnace. The descriptions of the furnaces list several mines that supplied ore to each furnace, indicating that these were larger and more permanent structures than the earlier log and ash furnaces. Litton (1854) states that log and ash furnaces previously had been used at the location of one of the Scotch hearth furnaces; log and ash furnaces may have been used earlier at at least two other locations where smelting is recorded as having been active before 1836, the first year the Scotch furnace is known to have been used in Washington County. Although Litton (1855) describes the location of Walton's Furnace only by saying that ore from Forche a Cortois Mines (a large area) was smelted, Park (2006) implies that it was near Manning's Furnace, and Robertson (1894b) lists two probably Scotch hearths at Webster (Palmer).

At least three types of reverbatory furnaces were used in Missouri: the previously described ash furnace, the Drummond furnace, also called the air furnace (Robertson, 1894b), and the Flintshire furnace, which was described by Ingalls (1908) as a "more highly developed form" of reverbatory furnace. The ore charge and the fuel are not in contact with each other in a reverbatory furnace, and a blast is not required. The ore is smelted by the heat that reflects, or "reverberates", off the walls of the furnace. The reverbatory furnace ran continuously rather than intermittently as was the case of the Scotch hearth and was therefore more economical, and produced more lead than the Scotch hearth

(Park, 2006). The recovery of lead by an air furnace was estimated by Robertson (1894a) and by Ingalls (1908) as 80-90 percent of the lead in the ore, similar to that of the Scotch hearth, but Winslow (1894) quotes an estimate of 63 percent recovery. Although the amount of slag produced was small (Robertson, 1894a), Ingalls (1908) estimates that the slag, which was generally thrown away, contained from 40 to 55 percent lead; Robertson (1894a) states that the loss of lead to the slag and by volatilization was 10 to 20 percent.

The Scotch hearths began to be replaced by (or were converted to) air furnaces in Missouri by about 1874 (Park, 2006), although Litton's (1855) mention of a reverbatory furnace at Bisch's Mine may mean that this was an early air furnace. Robertson (1894b) states that there were two Scotch hearths and a slag furnace at the Valles Mines (for the Valles Mines [proper?]) at that time, indicating that some Scotch hearths were still operating in 1894. Several air furnaces were in operation in Missouri by 1876, particularly in central Missouri (Robertson, 1894b), but apparently not yet in Washington County. Without giving locations, Winslow (1894) quotes an estimate of no air furnaces and two Scotch hearths operating in Washington County in 1876, one air furnace and two Scotch hearths in Jefferson County in 1876, and nine air furnaces and zero Scotch hearths in St. Francois County in 1876 (it is unclear if any of the air furnaces in St. Francois County were at the Valles Mines). Robertson (1894b) lists, with only approximate locations, eight air furnaces operating in 1894 in Washington County and one in St Francois County (with no specific location information, it is unclear if this furnace was at the Valles Mines). The air furnaces in Washington County are: Higginbothom Furnace at Fertile, which replaced a previous furnace at that location; James Long Furnace at Potosi; William Long Furnace at Potosi; Charles Moran Furnace at Richwoods; Palmer Lead Company Furnace (the "Palmer" furnace, or "Hazel Creek Furnace"; Park [2006]) at Palmer; Shibboleth Lead Company at Cadet; M and

S Union Company at Old Mines; and L. J. White Furnace at Old Mines. These eight furnaces are located only approximately on figure 8 using the locations described in Robertson (1894b).

In addition to the mostly Scotch hearth furnaces listed by Litton (1855) and the air furnaces listed by Robertson (1894b), there are a few other furnaces mentioned in various sources; some of these provide additional information with good location data, others are ambiguous, and a few furnace locations given in the IMOP database are at different locations than what is given in cited references or were not found in references. Winslow (1894) and Litton (1855) state that furnaces were operated by George Cresswell beginning in 1828 at two other locations prior to his construction of a Scotch hearth on Mineral Fork in 1838 (fig 8); the locations of these are not given accurately enough to show on figure 8, but given the early period of operation, these early furnaces probably were log and ash furnaces. Robertson (1894b) provides a cumulative lead production figure through early 1874 for two furnaces at or near Webster (Palmer). Given that air furnaces probably were not being operated in Washington County until 1876, these may be Litton's (1855) Manning's Scotch hearth and Walton's Scotch hearth (fig. 8). Park (2006) states that three air furnaces were operating at Palmer by 1887. One of these likely is the Palmer Furnace listed by Robertson (1894b), the location of which is well established (fig. 8); the location of the other two are not known and are shown on fig. 8 as unnamed furnaces near the town of Palmer. Robertson (1894b) provides some late 1870's lead production figures for Flynn's Furnace at Richwoods (fig 8), an air furnace. Robertson (1894b) mentions and provides a late 1870's lead-production figure for a Scotch hearth owned by J.P. and R.M. Bugg at Potosi (fig. 8). Winslow (1894) provides data for a small amount of cumulative lead production from 1872 to 1891 from the Abbyville Mining Company Furnace in northwestern Washington County (fig. 8; the IMOP database shows this as primarily an iron furnace). Winslow (1894) also provides data for a small amount of cumulative lead production from 1872 to 1891 from the Kingston Furnace in Washington County, but does not describe what kind of furnace it was or its location (because the IMOP database shows two furnaces called the Kingston Furnace at different locations, this furnace is not shown in figure 8). Park (2006) mentions and locates on a map the Edmonds & Wilcox Furnace and Mill near Richwoods (fig. 8), but it is not clear if this was a lead furnace, and no dates of operation are given. Park (2006) mentions a Cannon Creek Mine Furnace but provides no other information except that it may be the same as Murphey's Furnace (probably T & W Murphey's Furnace; fig. 8). A Flintshire furnace was operated for several years at the Frumet Mine in Jefferson County beginning in 1870 (Robertson, 1894b). The IMOP database lists a furnace at the Prairie Diggings (fig. 8), but the type of furnace is not given. The IMOP database lists a furnace of the Renault Lead Company and locates it about 3 mi northeast of the Palmer Lead Company furnace (fig. 8). The only other available reference to this company is Park (2006) who states that the company operated in the Palmer area from 1898 until about 1907, but he does not mention a furnace. The IMOP database also lists another possible furnace near the Renault Lead Company furnace. The IMOP database shows a log furnace at Gray's Mine (fig. 7) and what is probably a log furnace at Forche a Renault Mine (Mine Renault).

Winslow (1894) is the most recent report that discusses lead mining in the Southeast Missouri Barite District and the Valles Mines in a comprehensive manner, and information regarding the smelting of lead ores since then is not available. Air furnaces were being used in 1894, but it is not known if any other type of furnace came into use in the district later. Winslow (1894) describes the Cupola, or stack furnace, which Ingalls (1908) described as a blast furnace, but no mention is made of its use in the Southeast Missouri Barite District or at the Valles Mines. The Cupola furnace, which required large and constant supplies of ore and could smelt lower grade ore economically (Robertson, 1894a), was used to smelt ore from Mine La Motte and the Old Lead Belt, but would not have been well suited for the intermittent smelting of the higher grade feed from the smaller mines of the Southeast Missouri Barite

District. Beginning in 1892 a large lead smelter operated for over one hundred years at Herculaneum, Jefferson County, Missouri (fig. 8), smelting lead concentrate from the Old Lead Belt, Mine La Motte, and later, the Viburnum Trend Subdistricts of the Southeast Missouri Lead District.

The first zinc furnace in Missouri was the Hesselmeyer furnace built in Potosi in 1867 to smelt zinc ore from the Valles Mines (Winslow, 1894; Ingalls, 1908; Park, 2006). Zinc had become a greater source of profit than lead at the Valles Mines, but the furnace did not operate for very long (Ingalls, 1908). Much of the zinc ore apparently was shipped out of the area, either to a smelter in Carondelet in St. Louis (Park, 2006; Winslow, 1894a) or to other smelters; Robertson (1894b) lists several in Illinois, southwestern Missouri, and Kansas. Processing of zinc to zinc white (a paint pigment) was done at the Hopewell Furnace (fig. 8), Washington County, beginning in the mid 1870's, where lead was already being smelted in a Scotch hearth (Winslow, 1894). The IMOP database shows a furnace at the "Washington County Zinc Works", and also describes it as a "sorting plant near Hopewell". The IMOP database identifies Smith's Furnace at Evans Mine about two miles to the south of the Hopewell Furnace, and shows it as a zinc smelter. Winslow (1894) mentions surface diggings near Irondale and states that the Deggendorf Zinc Works was built in 1870 about two miles north of Irondale; this is shown on figure 8 at the IMOP location of the Deggendorf and Wills Mine (not identified on figure 7). In 1915-16 fifteen carloads of zinc carbonate ore were shipped from the Strawberry Diggings in the Palmer Mines area (fig. 7; Park, 2006; Killsgaard and others, 1967), but it is not stated where the ore was smelted.

For many years lead was transported by pack horses or wagons to ports on the Mississippi River for shipment to various markets. These ports were Ste. Genevieve in the early years, Herculaneum beginning in about 1808, and Selma (fig 2) also in the early 1800's, for which the Selma Road was built (not shown on figures). The road ran from the Shibboleth Mines at first, then was extended through Old

Mines to the Cresswell Furnace, and connecting roads were built to Potosi, Palmer, Hopewell, Cadet, Fertile, Frumet, and the Valle Mines (figs. 7 and 8; Park, 2006). Shipment of lead by wagons on the Selma Road and other roads continued for decades, and by the late 1840’s there were several other shipping ports on the Mississippi River (Winslow, 1894). Shipment of lead by railroad began in the 1850’s with the construction of the Iron Mountain Railroad from St. Louis to the Pilot Knob iron mine in Iron County, Missouri (fig. 1) south of the Southeast Missouri Barite District (Winslow, 1894). Other railroads were built beginning in the late 1870’s to ship lead concentrate from the mines of the Old Lead Belt, but may also have shipped some lead from the Southeast Missouri-Barite District and the Valles Mines. A rail spur was built in 1969 from Cadet to the Indian Creek Mine and later the Pea Ridge iron mine in northwestern Washington County (fig. 7).

Underground room and pillar mining methods were employed at lead mines in Washington County at the Indian Creek Subdistrict, the Viburnum No. 29 Mine of the Viburnum Trend Subdistrict, and probably the Irondale Subdistrict of the Southeast Missouri Lead District (fig. 7). The Indian Creek Subdistrict consisted of two mines (the Indian Creek Mine and the Goose Creek Mine) which operated from 1953 to 1982, with a shared lead concentrating mill and tailings lake but not a smelter (fig. 8). The Viburnum No. 29 Mine in southwestern Washington County began operations in 1964. It is one of three mines centered on the city of Viburnum in Iron County (fig. 1) with a central concentration mill but not a smelter. The mill’s tailings lake is outside the study area in Iron County on Indian Creek, a tributary of Courtois Creek which flows northward through southwestern Washington County. The Viburnum No 29 Mine is located along Indian Creek downstream from the tailings lake. The IMOP database shows that there was a blast furnace at the Irondale Mine in the Irondale Subdistrict (fig. 8).

Lead and Zinc Production and Losses

Lead and zinc production from the Southeast Missouri Barite District and the Valles Mines is not well documented but some production data and estimates are available. Most production figures in the literature are for specific mines, mining areas, or furnaces at various points in time (rather than for the entire history of a mine or furnace, though some data of this type are available), are different types of production (mine ore production or furnace metal production) and are of variable quality depending on the age of the mine or furnace, and the type of source (recorded, or reported by a mine owner or another person). There are many mines for which no production data or estimates are available.

The most comprehensive estimates of lead and zinc production through the late 1800's are in Winslow (1894); Wharton (1975) provides more recent production estimates that capture the entire period of mining. Winslow (1894) has tabulated estimates of tons of lead produced and tons of lead in the ore that was fed to the furnaces, and the same for zinc and zinc ore, by decade or longer period of time, and with cumulative production through 1893, for Washington, Jefferson, and St. Francois Counties. In most cases Winslow (1894) first estimated lead or zinc metal production and then applied an estimated furnace recovery rate to calculate the tons of lead or zinc in ore that was fed to the furnaces; in some cases he started with tons of metal in the ore and applied the furnace recovery rate to calculate metal production. The Valles Mines are in both Jefferson and St. Francois Counties, so it was not possible for Winslow (1894) to differentiate production from these mines by county; Winslow (1894) arbitrarily credited St. Francois County with all the Valles Mines production through 1879 and credited Jefferson County with all the Valles Mines production after that (table 3). Also, Winslow's (1894) tabulated production estimates for St. Francois County include production from early diggings in areas that would become the Old Lead Belt, and beginning in the 1860's, production from larger scale mines of the Old Lead Belt. Because Winslow (1894) also includes some details of production from specific mines in St. Francois County, it was possible to estimate for this report approximately how much of the St. Francois County lead production was from the Valles Mines. Winslow's (1894) tabulated estimates were used to construct table 3 which shows estimated lead content of the ore (tons of lead in the ore that was fed to the furnaces), tons of lead produced, zinc content of the ore (tons of zinc in the ore that was fed to the furnaces), and tons of zinc produced, by decade or longer period of time, and with cumulative production through 1893 for the combined Southeast Missouri Barite District and Valles Mines, by county. The production estimates for Washington County probably include the Irondale Subdistrict of the Southeast Missouri Lead District (fig. 1); Winslow (1894) describes these mines as surface diggings, so production through 1893 would not have been large and any larger-scale underground mine production from the Irondale subdistrict would have been after 1894. Buckley (1908) shows that 790 tons of lead concentrate was produced by the Irondale Lead company in 1902, after which the company was purchased by the Federal Lead Company, which operated mines in the Old Lead Belt; it is not possible to determine how much of the production of the Federal Lead Company in subsequent years came from the Irondale Subdistrict. Production data for the Indian Creek Subdistrict and the Viburnum No. 29 Mine of the Viburnum Trend Subdistrict are not included for Washington County, as these mines came into production much later than 1893.

Table 3. Table 3. Estimates of lead and zinc production from the combined Southeast Missouri Barite District and Valles Mines, and the Southeast Missouri Lead District

Table 3 shows estimated combined lead and zinc production from the Southeast Missouri Barite District and Valles Mines, by county, through 1893 (1892 for Jefferson County), modified from Winslow (1894). Most of the lead produced through 1893 came from Washington County, but there was more zinc produced in each of Jefferson and St. Francois Counties than Washington County. Table 3 shows that an estimated 103,000 tons of lead and 4,700 tons of zinc were produced in Washington County through 1893, 18,000 tons of lead and 12,000 tons of zinc were produced in Jefferson County through 1892, and 36,000 tons of lead and 9,000 tons of zinc were produced in St. Francois County through 1893, for a total of 157,000 tons of lead and 25,000 tons of zinc through 1893 (but not including production from Jefferson County in 1893; also, in addition to being just estimates, the figures for Jefferson and St. Francois Counties are inaccurate to the extent that Winslow [1894] was unable to split production from the Valles Mines by county and allocated all the production to one or the other county for different periods of time).

Lead and zinc mining continued after 1893, so Winslow's (1894) estimates do not show total production from the Southeast Missouri Barite District and Valles Mines, but captures most of the lead production; mining in the Southeast Missouri Barite District was declining as larger-scale underground mining in the Old Lead Belt increased. Ball (1916) describes lead mining in 1916 by stating that "mining methods of a century ago prevail", so at least some lead mining continued into the 1900's, and lead was sometimes recovered as a by-product of barite mining (which continued into the 1980's). Also, there was substantial zinc production after 1893, particularly from the Valles Mines in St. Francois and Jefferson Counties. Wharton (1975) uses Winslow's (1894) data and other data to provide estimates of cumulative lead and zinc production through 1948 from "Potosi-Eminence Mineralization" in what he calls the "Potosi-Palmer-Richwoods Subdistrict", which includes parts of Washington, Jefferson, and St. Francois Counties (exclusive of the Valles Mines), and, separately, from the Valles Mines. Although there may be some production from outlier mines that is not included, production from these two areas essentially is production from the Southeast Missouri Barite District and the Valles Mines. Wharton (1975) estimates that 150,000 tons of lead were produced from the "Potosi-Palmer-Richwoods Subdistrict" through 1945, and 30,000 tons of lead and 54,000 tons of zinc were produced from the

Valles Mines through 1948. Combining these two, Wharton's (1975) estimate of total production from the Southeast Missouri Barite District and Valles Mines through 1948 is 180,000 tons of lead and 54,000 tons of zinc (table 3), 23,000 tons more lead and 29,000 tons more zinc than the estimate of 157,000 tons of lead and 25,000 tons of zinc produced through 1893 (table 3). Wharton (1975) includes zinc production only from the Valles Mines; Winslow (1894) estimates 5,666 tons of zinc production that was not from the Valles Mines. These 5,666 tons of zinc are probably a minimum amount not included by Wharton (1975), so if 6,000 tons are added to his 54,000 tons of zinc, then the estimated zinc production from the Southeast Missouri Barite District and Valles Mines through 1948 is 60,000 tons (table 3). Except for some lead recovered during barite mining since 1948 (for which no estimate is available), the production of lead and zinc through 1948 is essentially all the lead and zinc produced during the history of the Southeast Missouri Barite District and Valles Mines (table 3). Whereas most of the lead was produced before 1893, there was more zinc produced after 1893 than before 1893. These figures are only rough estimates, but give an approximation of the lead and zinc production from the Southeast Missouri Barite District and Valles Mines.

Although the mines of the Southeast Missouri Barite District and Valles Mines were small compared to the mines of the Old Lead Belt and the Viburnum Trend, they were widespread, and mining throughout the district lasted for many years, from the early 1700's to at least the early 1900's (and later if lead as a byproduct of barite mining is considered). Production was not evenly distributed throughout the area; Ball (1916) estimates that about 55 percent of the lead production in Washington County was from mines around Potosi, and about 35 percent was from mines around Palmer (without defining these areas any further).

Using a density of lead of 709 lb/ft^3, the volumetric equivalent of the estimated 180,000 tons of lead produced in the Southeast Missouri Barite District and Valles Mines is a cube of lead about 80 ft on a side, or a football field of lead 10.6 ft high. Using a density of zinc of 445 lb/ft^3, the volumetric equivalent of the estimated 60,000 tons of zinc produced in the Southeast Missouri Barite District and Valles Mines is a cube of zinc almost 65 ft on a side, or a football field of zinc 5.6 ft high.

Considerable amounts of lead were lost during processing. The difference between the estimated total tons of lead in the furnace feed (241,000 tons) and the total tons of lead produced (157,000 tons) through 1893 (table 3) is 84,000 tons of lead lost to ashes, volatilization, or by some other process; 65 percent of the lead in the furnace feed was recovered and 35 percent was lost. These percentages applied to the estimated 180,000 tons of lead produced yield 277,000 tons of lead in the furnace feed (table 3) and 97,000 tons of lead lost. The unrecovered (lost) lead has a volumetric equivalent of a cube of lead about 65 ft on a side, or a football field of lead 5.7 ft high.

Considerable amounts of zinc also were lost during processing. The difference between the estimated total tons of zinc in the furnace feed (75,000 tons) and the total tons of zinc produced (25,000 tons) through 1893 (table 3) is 50,000 tons of zinc; 33 percent of the zinc in the furnace feed was recovered and 67 percent was lost, about twice as large a loss percentage as for lead. These percentages applied to the estimated 60,000 tons of zinc produced yield 180,000 tons of zinc in the furnace feed (table 3) and 120,000 tons of zinc lost. The unrecovered (lost) zinc has a volumetric equivalent of a cube of zinc about 81 ft on a side, or a football field of zinc about 11 ft high. It is interesting to note that while the estimated lead produced (180,000 tons) exceeded the estimated zinc produced (60,000 tons) by a factor of 3, the estimated zinc lost (120,000 tons) exceeded the estimated lead lost (97,000 tons) by a factor of about 1.2 because of the larger percentage loss of zinc than lead. Also, the volumetric equivalent of zinc lost was larger than the volumetric equivalent of lead lost by a factor of about 2 because the density of lead is greater than that of zinc. The loss of zinc during smelting was likely not as widespread in the study area as that of lead; although zinc was commonly associated with lead in the ore, it was not recovered until the 1860's, and most of its production was from the Valles Mines (estimated 54,000 tons of zinc out of an estimated 60,000 tons of zinc produced in the entire district). Also, although the estimated percentage of zinc lost during smelting (67 percent) was large, most of the zinc smelting appears to have occurred outside the district (Park, 2006; Robertson,1894b).

The estimates of lead and zinc losses presented above are losses during smelting, based on Winslow's (1894) estimates of the metal content of the feed to furnaces and the metal produced through 1893, and assuming that the percentage of metal lost, particularly zinc, was the same after 1893 as before 1893. The estimated losses do not include losses at the mine site during mining and preparation for smelting, such as the loss of fine-grained galena during hand cleaning, or the discarding of zinc ore before its value was known, for which no estimates are available.

The amount of rock and residuum that was mined for lead and zinc from the Southeast Missouri Barite District and Valles Mines is not known but is more than the amount of ore that was fed to the furnaces. The mined material that was brought to the surface consisted of ore and gangue minerals, dolomite, and clay, and was hand-cleaned to provide as pure a feed for the furnaces as possible. Table 3 shows, by county, the estimated lead content and zinc content of the ore fed to the furnaces through 1893, modified from Winslow (1894), not the amount of ore fed to the furnaces. Ingalls (1908) estimated that the grade of ore fed to the log furnaces was about 80 percent lead, that is, 80 percent of the furnace feed was lead; pure galena is about 87 percent lead. This contrasts with larger-scale underground disseminated-lead mines of, for example, the Viburnum Trend, where most of the material that goes to concentration mills is the host rock dolomite, with a few percent of lead and zinc.

The estimated production from the Southeast Missouri Lead District also is shown in table 3, for comparison with the combined production from the Southeast Missouri Barite District and Valles Mines. Schott (2012) estimates that 263 million tons of ore containing 2.9 percent lead (7.6 million tons of lead) and 0.3 percent zinc (800,000 tons of zinc) were mined from the Old Lead Belt, and 300 million tons of 5.8 percent lead (17.4 million tons of lead) and 1.1 percent zinc (3,300,000 tons of zinc) were mined from the Viburnum Trend through 2011 (table 3). Production from other subdistricts also is shown in table 3, and the total of these subdistricts (but not including what was a small amount of production from the Irondale Subdistrict) is 611,200,000 tons of ore containing 26,830,000 tons of lead and 4,200,000 tons of zinc. The estimated 180,000 tons of lead produced from the Southeast Missouri Barite District and Valles Mines is small compared the Southeast Missouri Lead District (the lead content of the Southeast Missouri Barite District and Valles Mines furnace feed [277,000 tons] was only about 1 percent of the lead content of the Southeast Missouri Lead District ore through 2011 [26,830,000 tons), but was still substantial. The estimated 180,000 tons of lead produced in the Southeast Missouri Barite District and Valles Mines is about 1.5 times the estimated 118,000 tons of lead produced in 2013 by the Doe Run Resources Corporation Herculaneum, Missouri lead smelter, which was supplied by six mines in the Viburnum Trend (U.S. Geological Survey, 2014). In earlier years, when richer ore was being mined in the Viburnum Trend and when mine production was greater, a single, large mine might produce about 1,800,000 tons of ore containing up to 10 percent lead in one year, with a lead content roughly equivalent to the estimated 180,000 tons of lead produced in all years from the Southeast Missouri Barite District and Valles Mines.

Barite Mining

Although barite was produced from the Valles Mines, its production was small compared to the Southeast Missouri Barite District, and barite mining at the Valles Mines was not as important as zinc or lead. For this reason, this section focuses mostly on barite mining in the Southeast Missouri Barite District.

Early barite hand mining was widespread but the locations of barite “diggings” are not well documented. Areas of later, mechanized mining in the study area are shown by spoil areas (strip mine areas) in figure 10 and barite tailings lakes in figure 11, both from the Missouri Geological Survey Mined Land Coverage (Cheryl Seeger, Missouri Geological survey, personal communication, October 27, 2015). It is possible that some of the tailing lakes are also sites of barite mining before mine tailings were placed there. Figure 10 also shows the locations of barite mines (with or without lead or zinc) in the IMOP database. Figure 11 also shows the locations of barite tailings lakes and processing plants in the IMOP database, and the locations of processing plants in Washington County given in Park (2006). While not capturing all barite mines, particularly the early diggings, figures 10 and 11 illustrate how widespread barite mining was in the Southeast Missouri Barite District. Figure 6 shows all sites of barite occurrence in the study area shown in the IMOP database-prospects and occurrences in addition to mines.

Figure 10. Map of the study area showing locations and types of mineralization of Southeast Missouri Barite District and Valles Mines barite mines.

Figure 11. Map of the study area showing locations of Southeast Missouri Barite District and Valles Mines barite processing plants and tailings lakes

Development of Barite Mining

Schoolcraft’s (1819) description of the early lead mines in Missouri includes the observation that barite “may be considered the proper matrix of the lead ore, as it is found imbedded in, and often completely enveloped by it”. Although Schoolcraft (1819) states that barite was used as a chemical reagent and as a flux for iron-ore smelting, it had no value to the early lead miners. The barite, or “tiff” as the miners called it, was extracted from the residuum during lead mining and for many years was tossed aside or back in the pit (Tarr, 1918) as part of the mine waste. Mining for barite in the United States began in Virginia and Connecticut in about 1845 (Brobst and Wagner, 1967), as barite was by then being used as a paint pigment. Mining for barite in Missouri may have started in about 1850 (Brobst and Wagner, 1967), but Litton (1855) did not describe barite as an economically important resource in southeastern Missouri, so the barite mining referred to by Brobst and Wagner (1967) may have been in central Missouri, where a barite mill reportedly was operating by 1866 (Tar, 1919). Barite mining in southeastern Missouri was active by at least the 1860's, as Showater (1963) states that barite mining near Potosi began near the end of the Civil War. Without saying where in Missouri, Tarr (1918) suggests that barite mining was well established in Missouri by the 1870's. Showalter (1963) describes barite mining from the 1860's to about 1905 as carried out on a small scale because there were few buyers. Mining was by hand, and increased after 1905 as more uses for barite were developed. Tarr (1918) lists thirty-nine uses of barite, including paint pigment, lithopone (a white pigment made from barite and zinc sulfide), putty, rubber (for added weight), and linoleum (also for added weight). The peak of hand mining was during the period from 1905 to the 1930's, when several thousand people were engaged in barite mining (Showalter, 1963).

Because barite and lead commonly occur together, the existence of large amounts of barite was known by the lead miners. For this reason many of the barite diggings were on land previously mined for lead, and waste from lead diggings was picked through to recover barite that had been left behind. New areas of barite were found when barite "float" was turned up by plowing (Harness and Barsigian, 1946), and from prospecting. A common prospecting practice was to drive a steel bar into the ground, withdraw it, and inspect the tip of the bar for white barite residue which would indicate the presence of barite in the subsurface (Park, 2006; Showalter, 1963). Barite was hand-mined over a large area, especially in Washington County. Tarr (1918) estimated that the area of the barite-lead district as of 1918 was about 250 mi^2, mostly in Washington County but also in Jefferson County. Buckley (1908) describes and shows on a map thirty-three areas of barite diggings within a few miles of Mineral Point in Washington County. It was estimated that good productive land produced 2,000-6,000 or more tons of barite per acre, that the ore (barite) grade was 4-7% and up to 25% in pockets, and that clay containing 125 lbs of barite per cubic yard could be mined profitably (Park, 2006).

An important development occurred around 1926 when barite began to be used as a weighting agent (drilling mud) for oil well drilling, leading to increased demand for barite; eventually 80-85 percent of the barite produced in Missouri was marketed as drilling mud, the remainder going to the chemical grade market (Wharton and others, 1969). Burford (1978) states that when the drilling mud market was realized, "Outsiders pushed in, corporations were formed, residents and speculators alike bought up thousands of acres of barite-bearing land in hopes of getting a quick profit. Farmers marked off sections to be mined". Mechanized strip mining of old barite diggings had begun at Mineral Point in 1924 (Dake, 1930) to recover barite left behind by hand mining, and large-scale washing plants were used to clean the clay from the barite. Hand-mining, however, continued to thrive; Weigel (1929), describing mining practices in 1929, stated that hand mining still accounted for well over half the barite production. Washer plants closed beginning in 1931 (Showalter, 1963), unable to compete with the cheap labor of hand digging during the Great Depression (Park, 2006). Muilenburg (1954) stated that nearly all the barite produced before 1937 was by hand mining. Mechanized mining and washing returned in the 1940's, in large part because of a 1939 Federal court affirmation of a National Labor Relations Board's decision that hand miners were employees of the landowner rather than independent contractors (Harness and Barsigian, 1946). Miners had been permitted to live in cabins on the land and pay the landowner a mining royalty, but following this decision landowners became reluctant to continue this practice, fearing higher labor costs, already high because nearby war industries were employing some workers. By the late 1960's there were 25-30 washer plants in Washington County owned by 10 companies, and most of the concentrates were processed at 4 grinding plants near Mineral Point, (Wharton, 1969). Park (2006) provides the locations of 30 washer plants and grinding plants in operation in the late 1960's (fig. 11). Wharton (1972) stated that 8 companies operated 15 mines and washer plants in Washington County in 1971, a smaller number of plants than just a few years earlier. Muilenburg (1954) estimates that the barite-mining areas of Washington and adjacent counties comprise about 75 mi^2 (of which he forecast 15,000 acres [23.4 mi^2] would be productive and available for mining) , an area smaller than the 250 mi^2 estimated by Tarr (1918), probably indicating that mechanized mining, while concentrated where it did occur, was not as widespread as hand mining. The strip-mined areas shown in figure 10 have a combined area of about 26.3 mi^2. The strip-mined areas is actually somewhat larger, as at least some of what is shown on figure 11 as tailings ponds (about 4.7 mi^2) had been mined and later used to store tailings; the combined area of strip mines and tailings lakes is about 31 mi^2.

Barite was last mined in Missouri in 1998 (Missouri Department of Natural Resources, 2012). Searls (2000) states that a grinding plant operated in Missouri in 2000 using stockpile from an idle mine, and Rueff (2003) shows a barite grinding plant in Washington County. This may be the same grinding plant that operated in 2009 in Washington County (Miller, 2011).

Barite Mining and Processing Methods

Most of the barite that was mined in the Southeast Missouri Barite District was from the residuum, and for many years the mining method was hand digging in the same way as earlier lead mining. Landowners leased their property to miners, or "tiff diggers" as they were known (Chaney, 1949), who paid a royalty to the landowner for the barite they mined. Miners commonly lived with their families on the land they were mining, living rent-free in small houses built by the landowner (Weigel, 1929).

A small pit, or shaft, was dug with pick and shovel from 4 to about 30 ft deep (Tarr, 1918; cover photograph), often going to bedrock. The shafts were 3 to 5 ft in diameter, but were square on top if cribbing was used (Weigel, 1929); cribbing appears to generally have not been necessary, as the pits remained open for years despite rains (Steel, 1910). The shafts were widened out at depth, undercutting the upper few feet of residuum, such that the shafts resembled an inverted mushroom (fig. 12). Instead of widening the bottom of the shaft in all directions, drifts were sometimes dug in the directions of the richest ore as far as the miner felt was safe, usually 4 to 8 ft. (Steel, 1910). Three drifts might be dug and intersect drifts from adjacent shafts to create pillars and aid in ventilation. Ventilation could be improved by starting a fire or placing heated rocks in one shaft, causing an updraft in that shaft and a downdraft in an intersecting shaft (Tarr, 1918). Once the upper ore had been mined to the extent possible the shaft would be deepened; alternately, sometimes the shaft would be dug to its total depth at first and then the upper ore would be mined by stoping a drift upward, allowing the roof of the drift to collapse (Steel, 1910).

Figure 12. Photographs showing barite diggings

When one shaft was completed a second was started in the most favorable direction, and then a third and so on. Eventually the shafts would be spread out over the field as a series of holes with accompanying mounds of red clay (McQueen and Grohskopf, 1933; fig. 12) and might have a regular pattern like a checkerboard (Steel, 1910). Each miner was generally allotted an area 60 ft square (Tarr, 1918) in which he tried to maximize the amount of ore removed. A large part of the ground was necessarily left behind as pillars and was not mined; Steel (1910) estimated that only about half of the barite was recovered.

Barite mining sometimes extended into the bedrock, but this required explosives and was more expensive, and the bedrock was mined only when enough lead ore was present to justify the added expense (Steel, 1910). Shafts followed a vertical fissure until a “cave” containing ore was reached, and drifts were mined following horizontal stringers of barite and galena, which sometimes led to more ore.

Miners commonly worked with one or more partners, including family members (Chaney, 1949). The miner dug for barite while his partner operated the windlass to hoist ore and waste material to the surface in a bucket, and processed the raw ore (figs. 12 and 13). Generally, all the excavated material was removed from the shaft, but sometimes the material was sorted in the shaft and the waste was left behind in an abandoned drift, and only the sorted ore was removed from the shaft; ore not sorted in the shaft was sorted above ground. The barite was spread out on the ground or on boards to dry, or dried over an open fire (Showalter, 1963). Once dried, the barite was “cobbed” to separate the clay and other impurities from the barite (Tarr, 1918; fig. 13) in much the same way as clay was separated from galena during lead mining. The barite was then placed in a “rattle box”, shaped somewhat like a baby’s cradle which, when rocked back and forth, forced the barite against metal spikes inside the rattle box, further cleaning the barite (fig. 14). Fine-grained material, consisting of waste material such as clay and iron oxides (Harness and Barsigian, 1946) and other materials, but also fine-grained barite, passed through holes in the bottom of the rattle box. Although galena was sometimes recovered as a byproduct, fine-grained galena also would have passed through the rattle box onto the ground (Missouri Department of Natural Resources, 2013).

Figure 13. Photographs showing hoisting barite ore to the surface, and cleaning and sorting the barite

Figure 14. Photographs showing stockpiles of cleaned barite.

The cleaned barite passed through several hands after processing. The barite was hauled by mule-drawn wagon or cart to merchants such as country stores where the barite was weighed and sold in exchange for other commodities (Tarr, 1918). The barite was stockpiled there and sold to a buyer with access to the railroad (fig. 14), who then sold it to a customer or to a larger selling company (Hill, 1917). Hill (1917) lists 16 individuals or companies with offices in Washington, Jefferson, or St. Francois Counties or in St. Louis who sold barite. One of these was the Point Milling and Manufacturing Company that, beginning in 1904 (Steel, 1910), operated a mill in Mineral Point (fig. 2) for manufacturing ground barite. The barite was crushed and ground to minus 200 mesh, washed to remove clay, treated in lead-lined tanks with sulfuric acid to remove iron oxide (bleaching process), washed again to remove the acid, dried, and packed in barrels and sacks (Steel, 1910; Tarr, 1918). Additional details of the operation of this mill and the bleaching process, using lead lined tanks, lead pipes, lead-lined tank cars, and sulfuric acid, are given in Steel (1910). This may be the same company, called the Point Mining and Milling Co. by Wharton (1972), that experimented with steam shovels at Mineral Point in 1904. This experiment was apparently short-lived, and it was not until about 1924 that mechanized mining became important.

Early mechanized mining techniques are described by Weigel (1929). Shovels with ¾- to 1½-cubic yard (yd^3) dippers and powered by steam, gasoline, or electricity were used to strip the ground to a depth of 12 to 15 ft (fig. 15). The entire thickness of residuum was processed without removing any non barite-bearing overburden that might be present. As the ground was relatively soft, blasting was not necessary. The shovels were not able to mine “cleanly” to the bedrock because of its uneven surface, so any barite remaining in the low spots between bedrock “pinnacles” was mined by hand. Shovels loaded ore onto 5-yd rail cars which were hauled as much as 2,500 ft to washer plants by gasoline-powered locomotives on rail lines that were extended into the mine pit as mining progressed.

Figure 15. Photographs showing mechanized barite strip mining

The processing (milling) of barite ore was a matter of washing the barite to remove the clay, breaking the pieces of ore to reduce their size and remove coarse waste rock, and then concentrating the barite. Weigel (1929) describes small, combined hand and mechanical washers that were portable and could be operated by two men. Ore was fed by hand from a wheel barrel or wagon to a single gasoline-powered log washer where clay was removed, and a jig was used to concentrate the barite. These could be moved from site to site as mining operations moved. Larger, more elaborate permanent washer plants were located at Mineral Point, Old Mines, Cadet (figs. 2 and 16) and Fountain Farm (not shown on figure 2) during these early years of mechanized mining (Weigel, 1929). Weigel (1929) describes two plants near Cadet where ore was dumped from elevated rail cars through grizzlies (which retained oversized boulders) into 30-ft long double log washers. Log washers consisted of paddles rotating around an axis (“log”) which, with the addition of water, removed clay from the ore. Overflow from the log washers was waste and went to a mud (tailings) pond. The washed ore was crushed to about ¾ in, and the barite was concentrated in jigs. The coarse jig tailings went to tailings piles or were used as railroad ballast, and the jig fines (“middlings”) went to gravity tables for further concentration (Weigel, 1929; Dake, 1930). The table concentrates typically had a higher grade (about 98 percent barite) than the jig concentrates. Weigel (1929) also describes the operations at another plant at Cadet where a somewhat different process was used, including the use of trommels for concentration before the ore went to jigs, a drag dewaterer, and other processes. Limonite, which can coat the barite, presented a problem because even after crushing its specific gravity is similar to that of barite, and much of the barite shipped from the district contained limonite. This was not a problem as an oil-well drilling weighting agent, but was a problem for other applications.

Figure 16. Photograph showing a barite mill.

As previously stated, this period of early mechanized barite mining was short-lived, and some hand-mining continued during this time. By the early 1930’s the washer plants had closed and all barite mining again was done by hand. This, again, lasted only a few years and by the 1940’s barite mining and processing was again mechanized, this time at a larger scale, and hand mining produced just a small percentage of the barite production from the district. Cheney (1949), in describing mining practices at the time, states that power shovels stripped the ore, which now was loaded onto trucks rather than rail cars. Stripping of non barite-bearing overburden was sometimes done. Trucks hauled the ore to washer plants that were normally located within about 2 mi of the mine. These washer plants were temporary and were moved as necessary to remain within a reasonable distance of the mine site. Chenney (1949) states that the ore was fed from hoppers to a primary crusher before going to the washer, or breaker, a step not described for earlier washer plants (Weigel, 1929; Dake, 1930), and a strong jet of water was used at this time to begin the process of removing the clay from the barite. Most of the breakers were a rotating “grizzly”, or ‘squirrel cage”, made of rails, into which the ore was fed. The barite, being a relatively soft mineral, would break into smaller pieces and fall through the spaces between the rails, leaving behind the harder silica minerals which went to waste dumps. The ore then went to double log washers where, as in earlier washer plants, any remaining clay was removed from the barite and sent as waste to tailings ponds. Next, a trammel screen was used to grind and further concentrate the barite. The ore then went to jigs for more concentration, and then to a rake classifier. Overflow material went to the tailings pond. Cheney (1949) states that there were more than 20 washer plants in the district, in addition to several grinding plants for additional grinding to smaller sizes. Apparently only some barite was ground, depending on its final use.

Harness and Barsigian (1946) describe the grinding and bleaching process used in the barite industry in the United States, with some reference to practices in Missouri. Barite that was not going to be bleached (which was not necessary for well drilling and some other uses) was ground dry, and barite that was to be bleached was ground wet. Wet grinding consisted of grinding 5/8- in jigged barite in a tube mill, and the ground barite was then thickened using a Dorr classifier, bleached, vacuum-filtered, dried in a kiln, and bagged. Bleaching was done using a hot solution of sulfuric acid to remove impurities such as iron minerals and lead sulfide (galena). The type of vessel used during this process is not specified; an earlier bleaching process used lead-lined tanks (Steel, 1910; Tarr, 1918). Later, magnetic separators were later used to remove iron oxides (Wharton and others, 1969).

Mining methods appear to have not changed much by 1957. Muilenburg (1957) states that exploration generally was not needed, as old barite shafts served as guides to strip mining. Some exploration probably was done, though, as Wharton (1986) mentions prospecting using backhoes, and power augers in a grid pattern, exploration methods that probably were not new then. Barite was found almost from the surface down in most places, so stripping of non-ore bearing overburden generally was not needed. In addition to diesel- or gasoline-powered shovels that had been used earlier, Muilenburg (1957) mentions the use of draglines. Excavation depth averaged 10 or15 ft and sometimes was 30 ft or more, and went to bedrock if the ore grade was high enough. Whereas ore in low spots between bedrock “pinnacles” was hand mined earlier (Weigel, 1929), Muilenburg (1957) states that this ore generally was not recovered and was lost to future mining by being covered by jig tailings used for building and maintaining roads in the mine pit. Ore continued to be hauled by trucks, and trucks commonly returned from the washer plant with a load of jig tailings. A new road was built each time the shovel or dragline was moved (fig. 17).

Figure 17. Aerial photographs of barite strip mine and tailings pond.

Muilenburg's (1957) description of the milling processes provides some additional details, but basic methods do not seem to have changed much since Chenney's (1949) description. A rotating breaker screen (which may be the same as the trommel screen mentioned by Chenney [1949]), was used to break up the barite into pieces that fell through the screen, thus continuing the process of separating the barite from the harder gangue material before going to the jigs. A jaw crusher was sometimes used in place of the rotating breaker screen. Large quantities of water were required for milling the barite. A plant processing 800-1,000 yards of ore to produce about 100 tons of barite concentrate in 24 hrs required 1,000-1,200 gallons per minute of water. About 800-900 gallons would be recirculated water, the remainder coming from dammed streams or pumped from wells. The process of impounding the tailings, which had been done since washer plants began to be used, is described by Muilenburg (1957). A dike would be built across a small valley to hold the tailings and waste water, and would be increased in height as necessary using waste from the washing process and any overburden that was stripped before recovering the ore. Some dikes were built across valleys that had already been mined for barite (Harness and Barsigian, 1946). Ponds could be many acres in size, particularly where the land was relatively flat, and took many years to dry (fig. 17). Harness and Barsigian (1946) state that older ponds had not completely dried, but had a strong enough crust to support a plow team for cultivation. Waste material not placed in tailings ponds was placed in mine pits (Missouri Department of Natural Resources, 2013)

By 1972 front end loaders were being used in addition to power shovels and less commonly dragline excavators (Wharton, 1972). Ore left in low spots in the bedrock surface was sometimes recovered using draglines, a practice previously done by hand (Weigel, 1929) but which later had been discontinued (Muilenburg, 1957). Abandoned pits were also re-mined when market conditions allowed it. Milling of ore was done generally by the same methods as described by Muilenburg (1957). Rotary breakers, log washers and breaker screens continued to be used; crushers, which had been used some earlier, were not used (Wharton, 1972). A typical washer plant could process 70-120 yards of ore per hour to produce 100-200 lbs of barite per yard of ore, and would require up to 5,000 gallons per minute of water. It is not stated by Wharton (1972), but probably most of this water would have been recirculated, as was the practice described by Muilenburg (1957). Wharton (1986) states that froth flotation was being attempted with the goal of recovering barite from the washer waste water that went to the tailings ponds and was known to contain barite. It was unclear at that time (1986) if this process would be economical, but mining of barite did not last for many years after 1986, so this process would not have been very widespread, if practiced at all.

Although lead was sometimes recovered while processing the barite, how often this was done and how much lead was recovered are unknown (lead production estimates in table 3 do not include this). Weigel (1977), describing washers at Valles Mines, states that it was common practice to place the log washer oversize on a picking belt where galena “nuggets” could be removed. Weigel (1977) also states that galena was recovered from the first jig cell at the “old” plants.

Barite Production, Losses, and Potential Reserves

Cumulative production of barite in Missouri since 1872, when some records began to be kept, is estimated at 13.4 million tons (Missouri Department of Natural Resources, 2012). Allowing for 5,000 -

10,000 tons per year from the 1860's through 1871 (Park, 2006), the total cumulative production of barite in Missouri is estimated at 13.5 million tons. The total barite production from the Central Missouri Barite District, where production ended in the 1950's, is estimated at 400,000 tons (Wharton and others, 1969), so the total production of barite from the Southeast Missouri Barite District and the Valles Mines is estimated to have been about 13.1 million tons.

Most of the barite production from the Southeast Missouri Barite District was from Washington County. For this reason, most authors, when referring to district production, refer only to production from Washington County, or from the "Washington County Barite District", or use the term "Washington County barite" or similar terminology without referencing production from Jefferson or St. Francois Counties (also, there was minor barite production from adjacent Franklin and Crawford Counties, which are not part of the Southeast Missouri Barite District). Wharton (1975) estimates that the barite production from the Valles Mines through 1974 was about 3,200 tons, just 0.027% of the estimated 11.828 million tons of combined barite production for the Southeast Missouri Barite District and the Valles Mines through 1974.

Because most of the barite production in Missouri was from the Southeast Missouri Barite District, statistics for Missouri barite production serve as a proxy for production from the district. A graph of Missouri barite production from 1872 to 1998 (fig. 18) shows that Missouri barite production increased, with some brief downturns, from the early 1900's to 1957 when it peaked at about 382,000 tons per year. Production was mostly strong for the next few years before dropping in the 1970's and 1980's. Barite mining in Missouri ceased in 1998 (Missouri Department of Natural Resources, 2012). Although a grinding plant was operating in Washington County in 2000 (Searls, 2000) and in 2009 (Miller, 2011), and Rueff (2003) shows a grinding plant in Washington County, figure 18 does not show any barite production since 1998. Missouri led the United States in barite production in most years from

1885 to 1971, after which Nevada had the most production (Missouri Department of Natural Resources, 2012).

Figure 18. Cumulative Missouri barite production, 1872-1998

Hand mining and processing of barite was inefficient. Estimates of barite recovery range from less than one-fourth (Muilenburg, 1954) to about half (Steel, 1910), as the "pillars" between the shafts in the residuum needed to be left unmined for stability. The hand cobbing of the barite at the surface probably also was inefficient, as it would have been difficult to recover small pieces of barite bound to drusy quartz or other gangue minerals. Wharton (1972) states that the fine-grained barite was either discarded or lost; the rattle box was used to concentrate the barite by removing clay, but some barite, being a relatively soft mineral at 3 to 3 ½ on the Mohs 1 to 10 scale of hardness (Hurlbut Jr., 1971) would have broken into smaller pieces and would have passed through the slots in the bottom of the rattle box and onto the ground. Some galena, also a soft mineral at 2.5 on the Mohs hardness scale, also would have broken into small pieces; these galena "fines" would have remained with the clay (Missouri Department of Natural Resources, 2013) and would have passed through the slots onto the ground. Whereas mechanized stripping did not leave pillars behind and was therefore more efficient than hand mining, ore was sometimes left behind, particularly in low areas between bedrock "highs"; pits were sometimes re-worked to recover additional barite (Wharton, 1972).

Wharton (1986) estimated that about 30% of the barite was lost during the milling process. Wharton (1972) estimates that about two-thirds of the lost barite was fine-grained and was discharged to the tailings ponds with the "slimes", the remainder being larger-grained barite that also was lost during processing. Most of this fine-grained barite loss occurred as overflow from the log washers (Wharton, 1972), but fine-grained barite also was lost during the jigging process (Muilenburg, 1957). Some galena was lost to the tailings ponds (Missouri Department of Natural Resources, 2013), but this has not been quantified.

Recognizing that the tailings ponds (lakes) contained a large amount of barite and might be considered a barite resource, the Missouri Geological Survey investigated the tailings ponds to determine the tonnage, grade, and distribution of barite in representative ponds, and to provide information about the tailings that could be used to develop methods to recover the barite (Wharton, 1972). A 1972 inventory of tailings ponds by the Missouri Geological Survey identified 67 ponds in the Southeast Missouri Barite District, 40 of which were classed as large (more than 500,000 cubic yards or 500,000 tons of tailings, one yard weighing roughly one ton dry weight). Four ponds were sampled using a drill rig, and samples were scanned using X-ray fluorescence spectrometry to determine barium concentrations, from which barite concentrations were calculated. Wet chemistry was used for control assays. Results from the four ponds were used to estimate that the 67 ponds contained almost 39 million tons (or yards) of tailings averaging about 5% barite, for a reserve of 1.935 million tons of barite. This is about 17% of the estimated 11.5 million tons of barite produced in the district through 1971, and represented about 10 years of supply at the rate of production in the 1960's. Metallurgical tests determined that about 50 percent of the barite is a minus 400-mesh size. A map showing the location of the 67 tailings ponds, and a detailed map and cross section of each of the 4 ponds showing locations of drill holes, barite grade and thickness at each drill location, and areas of different grades of barite in each pond are given in Wharton (1972). The barite concentrations were the largest near the points of mill discharge because of the large density of barite. For example, a 15-ft interval of tailings near an old mill site contained about 26 percent barite, whereas the tailings most distal from the point of discharge ranged from 1.5 to 2.5 percent barite. The 67 tailings ponds inventoried in 1972 are fewer than the 93 tailings ponds in the study area listed in the IMOP database. Although lead concentrations were not reported by Wharton (1971), its distribution in the tailings ponds would probably be similar because of the large density of lead minerals.

The ore deposits contained lead (and zinc) minerals as well as barite. It is not known how much lead was removed during barite mining, either by hand or mechanized mining and processing, how much lead was recovered, or how much lead went as fines to the tailing ponds or as coarse material to mine roads or was otherwise lost.

Summary

The Southeast Missouri Barite District and the Valles Mines are in Washington, Jefferson, and St. Francois Counties, Missouri. Barite and lead ore occur together in these surficial and near-surface ore deposits and were mined during separate, but overlapping times: lead first, then barite. Lead mining began in the early 1700's and continued through the 1800's and into the early 1900's. Lead mining was by hand and although it was on a small scale compared to modern mines, the Southeast Missouri Barite District was the most important lead-mining district in the United States for a number of years. Although lead and barite were mined from the Valles Mines, it is known more as a zinc-producing area. Lead mining in residuum (residual soil) resulted in widespread areas of small pits (also called "shafts" or "diggings"), and there was some underground lead mining in bedrock.

Barite was mined from the residuum using similar hand-mining methods for many years, also resulting in widespread areas of diggings but not underground mines. Mechanized strip mining of barite began in the 1920's, Barite mining continued for many years, and more barite was produced than lead. Barite production slowed by the 1980's, and there has not been any barite mining since 1998. Missouri led the United States in barite production in most years from 1885 to 1971. Mechanized barite mining resulted in large strip-mined areas and tailings ponds, which contain the waste product from barite mills.

The U.S. Environmental Protection Agency (USEPA) has determined that lead contamination of residential surface soils and groundwater occurs in Washington and Jefferson Counties. To provide information that would be helpful to the USEPA in determining the source of soil and groundwater contamination, the U.S. Geological Survey, in cooperation with the USEPA, investigated the geology and mining history of the Southeast Missouri Barite District and the Valles Mines in Washington, Jefferson, and St. Francois Counties, Missouri. A literature review was conducted for this report without any field investigation.

The Southeast Missouri Barite District does not include ore deposits of the Valles Mines. There are similarities between the two, but they are different primarily in two respects: 1) most of the mining at the Valles Mines was in bedrock, in contrast to the Southeast Missouri Barite District where most of the mining was in the residuum; and 2) unlike the Southeast Missouri Barite District, the Valles Mines was an important zinc-producing area, and barite was not as important as in the Southeast Missouri Barite District.

Zinc commonly occurs with lead in ore deposits in Missouri and elsewhere, Zinc occurs in the Southeast Missouri Barite District, but it is not as common as in other lead-mining areas. Conversely, zinc was the most important resource in the Valles Mines. Zinc was not recovered during the early years of lead mining because it was not an important resource at that time. Later, after the value of zinc was recognized, it was recovered at some mines, and was the primary metal recovered in a few mines, particularly the Valles Mines. Because zinc generally was of secondary importance if at all, the term "lead mining" is meant to be a general term which includes the recovery of zinc in some cases, and in a few cases copper.

The Cambrian-age Potosi Dolomite is the most important formation in the Southeast Missouri Barite District and the Valles Mines because the residuum derived from it hosts most of the barite and lead in the Southeast Missouri Barite District, and ore also is found in the formation. The Cambrian-age Eminence Dolomite conformably overlies the Potosi Dolomite, and is the second most important ore-bearing formation. Clayey residuum overlies the Cambrian- and Ordovician-age formations in the study area and is mostly clay, but also contains chert, sand and sandstone, and drusy quartz and chalcedony, particularly where the residuum is developed from the Potosi Dolomite.

Barite (barium sulfate) is a primary ore mineral; however, some barite is secondary. The primary, and most important lead ore mineral, is galena (lead sulfide). Secondary lead minerals are cerussite (lead carbonate; also called “dry bone” by the early miners), and anglesite (lead sulfate). These secondary lead minerals commonly occur as alteration products of galena, and locally were important ore minerals. The primary zinc ore mineral is sphalerite (zinc sulfide); smithsonite (zinc carbonate) is a secondary mineral that also was mined as an ore mineral, and was more important than sphalerite in some deposits, including the Valles Mines. Chalcopyrite (copper-iron sulfide) also occurs in the ore deposits as a primary mineral and was recovered in a few mines.

Most of the ore that occurs in bedrock is of one of two types of ore occurrence: a) “runs”, or “channels”, also called “pipes” and “pipe veins”, are deposits with a larger horizontal than vertical extent with the vertical extent ranging from a foot to 5 or 6 ft, and sometimes occurring in different levels, and b) vertical “crevice” ore, also called “fissures” and “veins”, are vertical, tabular deposits that pinch out with depth and form along joints, with a greater vertical than horizontal extent, and which also occur as cross veinlets. Breccia-filling ore also occurs as vertical tabular masses cementing either fault or solution breccia. Ore in bedrock is characterized by open-space filling and less commonly replacement of the host dolomite.

Because galena, sphalerite, and barite are less soluble than dolomite, chemical weathering of the dolomite bedrock resulted in the concentration of ore minerals in the residuum, and most of the barite and lead mining was in the residuum, which averages 10 to 15 ft thick. Barite and lead concentration can occur randomly distributed in the residuum or evenly distributed from top to bottom, but usually the richest ore was found at the bottom of the residuum near the bedrock surface. Early miners recognized rich "runs" or "leads" of irregular shape and extent alternating with less rich or barren ground. This has been interpreted as representing original concentrations in fractures or solution channels – removal of the dolomite by solution left the relatively insoluble ore in roughly the same position as it was in the dolomite.

Barite, known as "tiff" to the miners, varies in size from minute grains to large masses (up to several hundred pounds), but is more commonly in pieces from about 1 to about 10 inches in size. Ball tiff is a botryoidal form of barite with a radiating, bladed structure. Chalk tiff is a finely crystalline aggregate of barite. Galena occurs as cubes or aggregates of cubes, known as "block mineral" or "cog lead"; a lesser amount of octahedral galena is present. Galena usually occurs as small cubes disseminated in chalk tiff, and less so in ball tiff. However, galena was sometimes found in masses as large as several hundred pounds. Sphalerite occurs as layers and isolated clusters of black, greenish-black, light red and tan crystals.

Barite textural zoning and mineralogic zoning occurs in large, linear ore runs from 1 to at least 6 mi long and from 200 yards to 3 mi wide in the Southeast Missouri Barite District. Barite textural zoning consists of a central zone of coarsely-crystalline barite that grades (or sometimes more abruptly changes) outward to a zone of finely-crystalline barite. Mineralogic zoning coincides spatially with the barite-textural zoning, with sulfides concentrated mostly in the center of runs.

French missionaries and explorers were the first to encounter lead mines in Missouri, which was then part of French-controlled Louisiana Territory. In 1715, Sieur Antoine de La Motte led an expedition into Madison County that resulted in the discovery of lead ore at what would become Mine

La Motte, one of the major subdistricts of the Southeast Missouri Lead District. Lead was mined by Sieur de Renaudiere in 1719 at Cabanage de Renaudiere, which may mark the beginning of mining at what is known today as Old Mines, the first settlement in Washington County. A prospecting expedition in 1719-20 by Philippe Francois Renault and La Motte, resulted in the discovery of lead and the development of lead mines in the Southeast Missouri Barite District at Mine Renault (also called Forche a Renault Mine), at Old Mines, and at other places along the Big River, Mineral Fork and Forche a Renault Creek. Renault continued to mine until 1744 when his mines closed; lead mining continued but was sporadic until about the end of the 18th century. Sometime between 1775 and 1780, Francis Azor, called "The Breton" because of his birthplace in Brittany, France, and Peter Boyer discovered lead at the surface at what would become known as Mine a Breton (sometimes written as Mine a Burton), the name later changed to Potosi.

A major advancement in lead mining in Missouri was the arrival in 1798 of Moses Austin, an American, who transformed lead mining from a seasonal endeavor carried out between the end of the harvest and winter to a year around industry. Until this time most of the ore in the district was dug from shallow diggings. Austin sank the first shaft in Missouri to a depth of 80 ft in 1799, and erected a shot tower about one mi northwest of Potosi. Austin also established the port town of Herculaneum on the Mississippi River in 1809 and built a shot tower there.

Other mining areas in the Southeast Missouri Barite District were developed in the early part of the 19th century, including Fourche a Courtois in southwestern Washington County (also known as the Palmer Mines or the Shirley-Palmer area), the French Diggings and Mines-LeBaume at what would become known as the Richwoods Mines in northeastern Washington County. Zinc became a valuable resource after the Civil War, and the Valles Mines was an important supplier of zinc as well as lead, with at least some production up until the 1920's). The lead mines in southeastern Missouri continued to operate during the Civil War, though at a diminished rate of production. It is unclear if production decreased or remained more or less uniform after the war through the latter part of the 19th century, but it did decline in the early part of the 20th century as mining in the Old Lead Belt, Mine La Motte, and the Tri-State District expanded.

In the earliest days of mining, lead ore was probably simply removed from the surface of the soil. Lead mining in the Southeast Missouri Barite District and the Valles Mines was primitive by modern standards, and production at individual mines was small compared to the underground mines of the Old Lead Belt and Viburnum Trend The earliest lead mines were “diggings” (also called “pits” or “shafts”) in the residual soil. Round holes about 4 ft in diameter were dug with pick and shovel, and a hand windlass and bucket were used to hoist material to the surface. The shafts were normally, but not always, dug to bedrock where the ore was commonly concentrated, and drifts about 4 ft by 4 ft were dug a short distance away from the bottom of the shafts, undermining the residuum. The process was repeated a short distance away, until a large area was covered with pits. The first shaft that was more like a modern shaft was Austin’s shaft at Mine a Breton; later, more mining in the bedrock was done, with shafts as deep as 170 ft and up to several hundred feet of lateral drifts.

The material brought to the surface consisted of lead ore, which was mostly galena, but it also had lesser quantities of cerussite and anglesite mixed with clay, dolomite and associated minerals, including druzy quartz, zinc ore and barite. Galena was cleaned by hand by “cobbing” with a hammer to remove as much clay and other non-ore material as possible to prepare the galena for smelting, and the remaining “waste” material was discarded in dumps. This included cerussite, anglesite, zinc ore and barite, until the value of these minerals was realized and they also were recovered.

Smelting of the lead ore to elemental lead was first done using a log hearth, also called a log furnace, and was the only type of furnace used until 1798. Log furnaces were probably built wherever there was mining; there probably were many log furnaces in the Southeast Missouri Barite District and the Valles Mines. Log furnaces were inefficient; estimates have been made that only about 50 percent of the lead in the ore was recovered, the remainder was lost to the ashes (slags) and to volatilization. About twenty log furnaces were in operation near Potosi when Moses Austin arrived in 1798. Austin built two, more efficient reverbatory furnaces, one for smelting primary ore, the other for smelting ashes (called an "ash furnace"). An ash furnace thus supplemented the log furnace. Log and ash furnaces, sometimes collectively termed a "log and ash furnace" were used in Missouri for many years but were gradually replaced by other furnaces, including the Scotch hearth. Estimates have been made that the recovery of lead by a Scotch hearth was 80-90 percent of the lead in the ore with 10-20 percent loss to slag and volatilization, but estimates of 67 and 70 percent recovery have been made. At least three types of reverbatory furnaces were used in Missouri: the previously described ash furnace, the Drummond furnace, also called the air furnace, and the Flintshire furnace. Different estimates of the recovery of lead by an air furnace are 80-90 percent of the lead in the ore, and 63 percent. Although the amount of slag produced was small, it has been estimated that the slag, which was generally thrown away, contained 40-55 percent lead.

The first zinc furnace in Missouri was the Hesselmeyer furnace built in Potosi in 1867 to smelt zinc ore from the Valles Mines. Zinc had become a greater source of profit than lead at the Valles Mines, but the furnace did not operate for very long. At least some of the zinc ore apparently was shipped out of the district, either to a smelter in Carondelet in St. Louis or to other smelters.

The total production from the Southeast Missouri Barite District and the Valles Mines is estimated at 180,000 tons of lead and 60,000 tons of zinc. Whereas most of the lead from the district was produced before 1893, there was more zinc produced after 1893 than before 1893. The volumetric equivalent of the estimated 180,000 tons of lead is a cube of lead about 80 ft on a side, or a football field of lead 10.6 ft high. The volumetric equivalent of the estimated 60,000 tons of zinc is a cube of zinc almost 65 ft on a side, or a football field of zinc 5.6 ft high. Considerable amounts of lead and zinc were lost during processing. An estimated 97,000 tons of lead was lost with a volumetric equivalent of a cube of lead about 65 ft on a side, or a football field of lead 5.7 ft high. An estimated 120,000 tons of zinc was lost, with a volumetric equivalent of a cube of zinc about 81 ft on a side, or a football field of zinc about 11 ft high. The loss of zinc during smelting was likely not as widespread in the study area as that of lead; most of its production was from the Valles Mines. Also, some of the zinc smelting appears to have occurred outside the district. The estimated losses do not include losses at the mine site during mining and preparation for smelting, such as the loss of fine-grained galena during hand cleaning or the discarding of zinc ore before its value was known, for which no estimates are available.

Barite mining in southeastern Missouri was active by at least the 1860's. Mining was by hand, and increased after 1905 as more uses for barite were developed. The peak of hand mining was during the period from 1905 to the 1930's, when several thousand people were engaged in barite mining. An important development occurred around 1926 when barite began to be used as a weighting agent (drilling mud) for oil well drilling, leading to increased demand for barite. Mechanized strip mining of old barite diggings began in 1924 to recover barite left behind by hand mining, and large-scale washing plants were used to clean the clay from the barite. Hand-mining, however, continued to thrive, and washer plants began to close in 1931, unable to compete with cheap labor of hand mining during the Great Depression. Nearly all the barite produced before 1937 was by hand mining. Mechanized mining and washing returned in the 1940's, and barite was last mined in Missouri in 1998.

Most of the barite that was mined in the Southeast Missouri Barite District was from the residuum, and for many years the mining method was hand digging in the same way as earlier lead mining. When one shaft was completed a second was started in the most favorable direction, and then a third and so on. Eventually the shafts would be spread out over the field as a series of holes with accompanying mounds of red clay. Barite also was “cobbed” to separate the clay and other impurities from the barite in much the same way as clay was separated from galena during lead mining. The barite was then placed in a “rattle box”, shaped somewhat like a baby’s cradle which, when rocked back and forth, forced the barite against metal spikes inside the rattle box, further cleaning the barite.

Early mechanized mining used shovels powered by steam, gasoline, or electricity to strip the ground to a depth of 12 to 15 ft, and ore was loaded onto rail cars for shipment to washer plants. The processing (milling) of barite ore was a matter of washing the barite to remove the clay, breaking the pieces of ore to reduce their size and remove coarse waste rock, and then concentrating the barite. Clay was removed from the barite using a log washer, and a jig was used to concentrate the barite. These could be moved from site to site as mining operations moved. Log washers consisted of paddles rotating around an axis (“log”) which, with the addition of water, removed clay from the ore. Overflow from the log washers was waste and went to a mud (tailings) pond. The coarse jig tailings went to tailings piles or were used as railroad ballast, and later roads, within the mine pit. By the 1940’s barite mining and processing was mechanized at a larger scale, using draglines and later front end loaders to strip the ore, and trucks rather than rail cars for shipment to washer plants. Some barite was ground, depending on its final use, and some ground barite was bleached using a hot solution of sulfuric acid to remove impurities such as iron minerals and lead sulfide (galena). An earlier bleaching process used lead-lined tanks.

Large quantities of water were required for milling the barite; some was recirculated water, the remainder coming from dammed streams or pumped from wells. The process of impounding the tailings had been done since washer plants began to be used. A dike would be built across a small valley to hold the tailings and waste water, and would be increased in height as necessary using waste from the washing process and any overburden that was stripped before recovering the ore. Some dikes were built across valleys that had already been mined for barite.

The total production of barite from the Southeast Missouri Barite District and the Valles Mines is estimated to have been about 13.1 million tons. Most of the barite production was from Washington County. Hand mining and processing of barite was inefficient. Estimates of barite recovery range from less than one-fourth to about half, as “pillars” between the shafts in the residuum needed to be left unmined for stability. Some barite would have broken into smaller pieces in the rattle box and would have passed through the slots and onto the ground. Some galena also would have broken into small pieces and would have passed through the slots onto the ground. With mechanized mining, large amounts of barite were lost during the milling process. It has been estimated that about 30% of the barite was lost, and that about two-thirds of the lost barite was fine-grained and was discharged to the tailings ponds with the “slimes”, the remainder being larger-grained barite that also was lost during processing. Some galena was lost to the tailings ponds.

A 1972 inventory of tailings ponds by the Missouri Geological Survey identified 67 ponds in the Southeast Missouri Barite District. Four of the ponds were sampled using a drill rig, and X-ray fluorescence spectrometry was used to determine barium concentrations, from which barite concentrations were calculated. Results from the four ponds were used to estimate that the 67 ponds contained almost 39 million tons (or yards) of tailings averaging about 5% barite, for a potential reserve of 1.935 million tons of barite. The 67 tailings ponds inventoried in 1972 are fewer than the 93 tailings ponds currently (2016) documented in the study area.

The ore deposits contained lead (and zinc) minerals as well as barite. It is not known how much lead was removed during barite mining, either by hand or mechanized mining and processing, how much lead was recovered, or how much lead went as fines to the tailing ponds or as coarse material to mine roads or was otherwise lost.

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